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HydroDog: A Quadruped Robot Actuated by Soft, Fluidic Muscles

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HydroDog: A Quadruped Robot Actuated by Soft Fluidic Muscles

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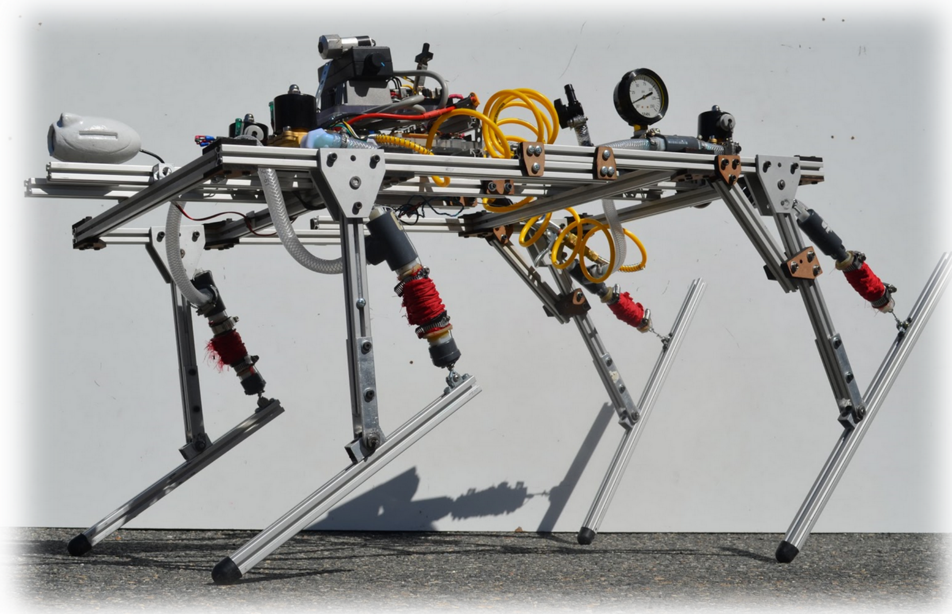

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	Reconfigurable Test Platform	Fitzgerald
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Contents

Acknowledgements **1**

Authorship **2**

Executive Summary **10**

1 - Introduction **12**

2 - Background **15**

2.1 Motivations for Legged Robots 15

2.1.1 Mobility 15

2.1.2 Efficiency 17

2.1.3 Biomimicry 17

2.1.4 Types of Legged Systems 18

2.1.5 System Characteristics by Number of Legs 19

2.1.6 Advantages of Quadrupeds for Research 21

2.2 Current State of the Art 22

2.2.1 Existing Quadruped Robots 22

2.2.2 Hydro-Muscles as an Actuator for Legged Robots 23

2.2.3 Comparison of Actuators by Type 25

3 - Project Objectives **26**

3.1 Determination of Design Specifications 26

3.1.1 Size and Weight 26

3.1.2 Cost 26

3.1.3 Actuation 27

3.1.4 Locomotion 27

3.1.5 Reconfigurability 27

3.1.6 Future Robotics Kinematics Platform 28

3.2 Project Scope and Limitations 28

4 - Design and Construction **30**
4.1 Reconfigurable Construction System . . . 30
4.1.1 80/20^{TM} . . . 31
4.1.2 Skeleton Design . . . 33
4.2 Modelling and Simulation . . . 34
4.3 Actuation System . . . 36
4.3.1 Power Augmentation . . . 38
4.3.2 Compliance and Incompressibility . . . 41
4.3.3 Control . . . 43
4.3.4 Fabrication . . . 44
4.3.5 Final Construction . . . 51
4.3.6 Evaluation and Verification . . . 52
4.3.7 Parallel Operation . . . 54
4.4 Fluidic System (Power Transmission) . . . 56
4.4.1 Pressure . . . 57
4.4.2 Flow . . . 57
4.4.3 Standardization . . . 60
4.4.4 Weight . . . 61
4.4.5 Accumulator . . . 62
4.4.6 Reservoir . . . 63
4.4.7 Hydraulic . . . 64
4.5 Dynamics . . . 65
4.6 Electrical System . . . 67
4.6.1 Power Requirements . . . 67
4.6.2 Power Supply . . . 68
4.6.3 Speed Controller . . . 68
4.6.4 Voltage Regulation . . . 69
4.6.5 Indicators . . . 69
4.6.6 Fuse Protection . . . 69
4.7 Sensing and Control Circuitry . . . 69
4.7.1 Sensors . . . 69
4.7.2 Control Circuit . . . 70
4.7.3 Microcontroller . . . 71

4.8 Software System 72
4.8.1 Open-Loop Control 72
4.8.2 Closed-Loop Control 74

5 - Testing, Iteration, and Results **78**
5.1 Methodology for Fluidic System Preparation 78
5.2 First Test 79
5.2.1 Setup 79
5.2.2 Response 80
5.2.3 Analysis 81
5.3 Second Test 81
5.3.1 Setup 81
5.3.2 Response 82
5.3.3 Analysis 82
5.4 Third Test 82
5.4.1 Setup 82
5.4.2 Response 83
5.4.3 Analysis 84
5.5 Fourth Test 84
5.5.1 Setup 84
5.5.2 Response 84
5.5.3 Analysis 85
5.6 Fifth Test 86
5.6.1 Setup 86
5.6.2 Response 86
5.6.3 Analysis 86
5.7 Sixth Test 87
5.7.1 Setup 87
5.7.2 Response 87
5.7.3 Analysis 88
5.8 Variables 88

6 - Conclusions **91**
6.1 Actuation and Locomotion 91
6.1.1 Comparison of Hydraulic and Pneumatic Fluidics 91
6.2 Control 92
6.3 Project Logistics - Weight, Cost, and Size 93
6.4 Reconfigurable Test Platform 93
6.5 Future Work and Recommendations 93

7 - Outreach and Presentation **95**
7.1 Vecna Robot Race 95
7.2 Cambridge Science Festival 2015 96
7.3 References 96
.1 Appendix 98
.1.1 Code Example 98

List of Figures

2.1 Types of quadruped gaits 21
2.2 A Bounding Quadruped Robot from the MIT Leg Lab 22
2.3 A quadruped robot built at WPI 23
2.4 An actuated arm from a previous Hydro-muscle project 24
4.5 Rendering of 80/20^{TM} Aluminum Extrusion 32
4.6 Top View of Skeleton 34
4.7 Side View of Skeleton 34
4.8 HydroDog Model in WorkingModel2D 36
4.9 Drawing of a Hydro-muscle supply system 36
4.10 Image of a McKibben muscle in various states 39
4.11 Diagram of a different hydro-muscle states 39
4.12 Abstract mechanical model of hydro-muscle operation 40
4.13 How hydro-muscles work 40
4.14 Physical parameters of an elastomeric tube 45
4.15 How hydro-muscles work 47
4.16 Nylon Tubular Webbing 47
4.17 Elastic constraining "uber-hose" sheathing 48
4.18 3D Printed hydro-muscle components 50
4.19 Hydo-muscle construction method 52
4.20 Image of final hydro-muscle 52
4.21 Muscle tests - Length vs. Pressure 53
4.22 Muscle - Volume vs. Length 54
4.23 Dual-rear muscle configuration 56
4.24 Detailed Diagram of the Fluidic System 61
4.25 Diagram of a constant-pressure accumulator 63
4.26 A CamelBak flexible fluid reservoir 64
4.27 Hip-Muscle Actuation for HydroDog 66
4.28 Dynamics of HydroDog 67
4.29 Schematic of the primary electrical system 71
4.30 Open-loop flowchart 74

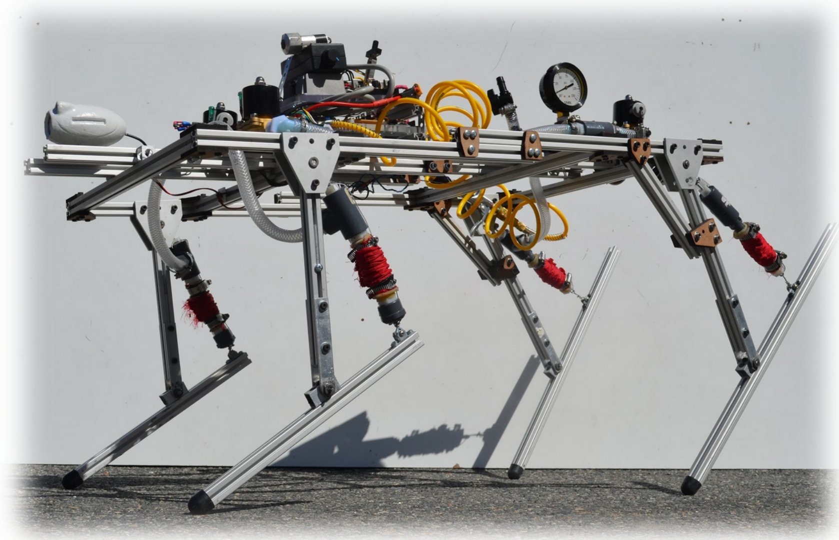
4.31 Closed-loop flowchart 75
4.32 Bounding Controller 77
5.33 The experimental setup 80
5.34 Test 1 jump 81
5.35 Test 3 Response 83
5.36 Test 4 Response 85
5.37 Test 5 Response 86
5.38 Test 6 Response 88
5.39 Geometric variables on the skeleton 89
7.40 Vecna race 95
7.41 Cambridge Science Festival 96

List of Tables

4.1 Hydro-muscle Pressure, Length, and Volume 53
4.2 Power requirements by component type 67
4.3 Physical quantities to be measured, by sensor 70
4.4 Control Table for valves 72
5.5 Geometric Variables 89
5.6 Final Iteration Dimensions 90

Executive Summary

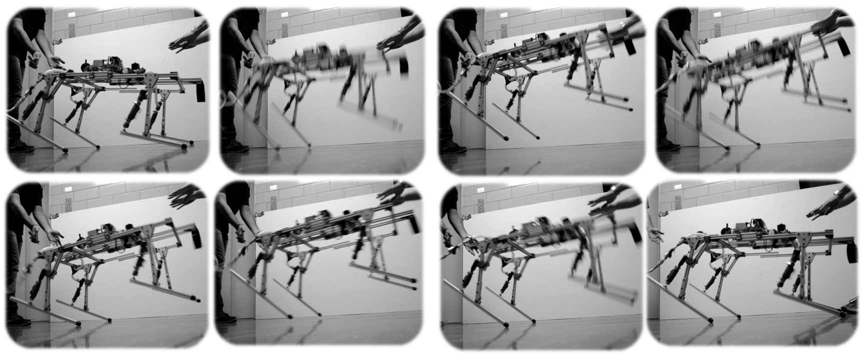
This report provides a detailed account of a Major Qualifying Project focused on the design, construction, testing, and optimization of a quadrupedal robotic platform. A review of the current state of the art in legged robotics is presented and discussed, followed by a definition of the Project Objectives and design specifications. These specifications include: limitations on system size and cost, the requirement to use hydro-muscles as the primary actuator, the implementation of a reconfigurable skeletal platform. A brief overview of overall project scope and limitations follows. The next chapter details the engineering and design process behind the skeletal, actuation, and control systems on the robot. Following this chapter is a detailed presentation of the testing and iteration methodology, in conjunction with the results of each test respectively.



The team constructed a highly modular, highly reconfigurable skeleton made mostly with extruded aluminum bars. This extrusion allowed the team to completely reconfigure the geometry of the skeleton and iterate a test in less than 5 minutes.

This skeletal platform is powered by a novel linear actuation system called "hydro-muscles", which are latex tubes that expand and contract when pressurized with a working fluid. This project tested hydro-muscle actuation using water with an on-board pump and then air with an off board compressor as working fluids.

Both fluids show promise for different applications. Being incompressible, water proved to be a viable choice for future fine position control applications, but its density and viscosity present an issue for high-power applications. Air shows promise for very high power because it allows hydro-muscles to contract explosively, but its compressible nature might hinder fine position control.



A wide array of kinematic configurations where tested, with an equally wide spectrum of success. The most successful jump performed by the robot achieved a height of about 25 cm of ground clearance and 29 cm of forward motion.

1 - Introduction

To build robots that can effectively move through the environment without human assistance has been a longstanding goal and area of research for scientists and engineers. The latter-half of the 20th century introduced unprecedented advances in computational power and better batteries with higher energy-densities, unlocking new possibilities in the field of robotics and thus making machines with high-mobility a tangible goal. A problem became apparent almost simultaneously to these advances, the problem of using wheeled machines in a developed world designed around the human bipeds who inhabit it.

Legged robots can reach locations that wheeled systems can not. In order for a robot to work alongside humans successfully, it must be able to operate in an environment designed for legged creatures. A robot should not be limited to flat floors and ramps; it should be able to climb stairs, step over obstacles, and navigate uneven terrain.

Early implementations of legged robots were almost exclusively based on a static gait as a movement strategy. This approach is simple and effective, as the only requirement for stability is to keep the systems center of mass (COM) above and within the virtual support polygon defined by the area within the ground contact points. This is based on the assumption that the momentum developed by the components of the system in the static gait are negligible. Static walking has continued to see implementation across a wide variety of robotic platforms, however the inherent limitations of this approach have motivated extensive research into dynamic methods of motion.

Even with the aforementioned advances in computation and power, the complexity of movements achievable by dynamic-gait walking robots has still been fairly limited. In the few cases where engineers were able to achieve a stable and dynamic gait, the machines were either umbilically tethered to a computer and power source, or prohibitively expensive to build and maintain. However, these robots did demonstrate that an untethered, stable, dynamic, and cost-effective robot was not far outside the realm of possibility, and will be further discussed in Section 2.2.

Recently, the field of legged robotics has progressed away from the use of off-board hydraulic pumps and towards the use of powerful, on-board power plants such as internal combustion engines. While this has resulted in new achievements in strength and mobility, it has also lead to a drastically increased cost of hardware as well as other practical concerns such as safety and accessibility.

This report documents the efforts of a team composed of three senior undergraduate engineering students at Worcester Polytechnic Institute to overcome the difficulties associated with dynamic legged motion through the exploitation of desirable passive mechanical characteristics and an efficient actuation system. Here, the process of design, construction and testing of a quadruped robot with an dynamic and energetic bounding gait is presented. The following chapters will detail the steps taken to design a robot capable of forward movement by virtue of the novel artificial latex "Hydro-Muscles". The report outlines the design and performance specifications of the robot, and chronicles the four major iterations of its construction.

In difference to many other previous undertakings of this type, the authors decided to design a system capable of early fundamental mechanical completion and extensive field modification. This practice reduces the necessity of advanced simulation typical of legged robot in the design stage. The challenges encountered during this Major Qualifying Project were diverse in magnitude; some were small, yet challenging logistical puzzles to solve, whereas as others required fundamental re-evaluations of basic project assumptions. These challenges and the methods by which the authors addressed them are detailed in this report, as well as the robot's final performance characteristics. The authors have taken care to address this report primarily to the future MQP teams who will benefit from a clear, brief, and concise report containing the lessons that were learned through practical experimentation and iteration. Contained in Section 9.5 is a non-exhaustive list of recommendations that a future team will benefit from examining.

Important considerations such as weight, cost, capability, and expandability are also discussed here in the context of choosing realistic goals at the start of a project involving legged locomotion. Although a section of this type is not strictly in-line with the conventions of a technical report, it is the opinion of the authors that this step has such a critical bearing to the rest of the design decisions that it must not be neglected. Functional legged system are challenging to design and implement, however the motivations that justify them are numerous, and will be discussed in the next chapter.

2 - Background

2.1 Motivations for Legged Robots

The field of robotics is largely dominated by machines that implement simple wheeled configuration effectively and do not require further advancement. Previously, it has been difficult to justify confrontation of the complexities and challenges associated with creating practical legged robotic systems. However, as technology has progressed, certain advances have led engineers and researchers to conclude that not only are these systems feasible, they are advantageous. The energy density of batteries has been a field of progress, in addition to improvements in computational systems and materials science. The second half of the 20th century presents a new frontier in robotics, one where robots walk like their biological counterparts. With the feasibility of legged systems realized, the advantages of such systems become more apparent and desirable. The first of these advantages is mobility, the ability to move from one place to another under the machine's own power. Legged systems can go where wheeled systems can not, and can adapt to many environments. Efficiency is also a consideration; since legged systems can traverse more featured terrain than legged systems, the ability to take a shorter route to a goal location is now present. This can be done while moving in a manner that reclaims energy during motion, or uses almost none at all. Another motivation that has driven many scientists and engineers to build legged robots is biomimicry, the act of emulating existing natural systems with the intent of inheriting the advantages and the benefit of countless years of evolutionary refinement. These three advantages, mobility, efficiency, and biomimicry are what verify the need for robots that walk, and will be discussed individually here.

2.1.1 Mobility

The natural processes of nature have resulted in a vast variety of different locomotion systems for land. Depending on the environment, these systems have been optimized for speed, climbing, leaping, and many other tasks. A solution that evolution did not yield is wheels, at least not by the macro-functional definition to which wheels are usually held. If the primary criterion by which to evaluate a locomotion system is simplicity, then wheels are difficult to contest as superior. Therefore it is natural that the vast majority of robotic systems that exist today implement some form of wheeled locomotion. This is not strictly problematic, because as the infrastructure of humankind grows, the assumption of a robot's accessibility to environments with flat floors and 90 degree world geometry becomes more justified. However, humans do not exclusively operate in simplified environments; stairs, for example, are an example of a unique challenge that must be addressed if the robot is to be useful in a human environment. A wheeled robot will not be able to climb a stairs unless its wheel radius is larger than the height of the step - a dimension that renders such wheels large cumbersome. Treaded or "tracked" platforms are usually able to overcome stairs, however the mechanical simplicity is lost to some extent on the additional components required for a tracked platform. When considering an environment not designed for humans, such as a forest floor, mountain, muddy ravine, or a even a tree, the limitation of wheels and tracks become even more apparent. Legged systems solve this problem through their absence of a requirement for a continuous environment to traverse. Discontinuities do not represent an obstruction because the ground contact of the robot's feet are themselves discontinuous.

An simple example illustrating this is a wide river, with several stones defining a path across it. A wheeled system will fail here, as the discontinuities between the stones will represent impassable points. In contrast, an adaptive legged system can sequentially lift and place its feet such that the discontinuities of the ground contact and the discontinuities of the ground are synchronized.

Situations such as these are numerous in the real world, therefore a legged system with the aforementioned adaptive capabilities is desirable in comparison to a wheeled system.

It should be noted that the methods of locomotion are not limited to that of wheels and legs. Aerial vehicles such as quadrotors and planes are also capable of serving as the locomotion portion of a robotic system. The benefits of systems such as these include mechanical simplicity, and the ability to circumvent ground-related issues entirely by simply flying over obstacles. However, these advantages come at the cost of efficiency. Continuously resisting the pull of gravity while maintaining the "dexterity" required to perform useful tasks for any appreciable period of time requires an immense energy source. Additionally, aerial vehicles have a very low payload capacity when compared to wheeled or legged systems. Aerial vehicles are less efficient for performing near-ground tasks than legged systems, which introduces the next major advantage of robots that can walk: efficiency.

2.1.2 Efficiency

The technology surrounding energy storage has improved drastically since the turn of the century. Newer batteries with chemistry such as Lithium Polymer (LiPo) are enabling robots to run longer and more energetically than with previous technologies such as Nickel-metal Hydride (NiMH) and Lead Acid. These advancements however are not yet so substantial that system efficiency can be neglected. Legged robots can be designed such that they exhibit passive dynamic motion characteristics, meaning that the forward momentum of the robot can be used to power the next leg swing-phase, and springs within the legs can re-claim some of the energy that would normally be lost during foot impact. Although several of the most widely-known successful implementations of robot legged locomotion rely on precise position control and force vector calculations, some researchers have looked to the field of passive dynamics to reach higher efficiency. These machines are smaller and simpler than their position controlled counterparts, but they utilize well-designed dynamic tendencies to create equivalently life-like gaits for only a fraction of the electrical energy input. Wheeled systems also have the ability to reclaim energy during braking and coasting, but forward motion can not be sustained without constant energy input. Moreover, if one considers a slightly different definition of efficiency, one where going a shorter unit distance to the same goal constitutes a higher efficiency, then legs have the potential to be more efficient since an obstacle does not automatically impose a detour.

A well-designed legged robot will maximize the work it can perform for the same amount of input energy. Efficiency is, in and of itself, an act of biomimicry, which presents the opportunity to derive important lessons from the process of evolution.

2.1.3 Biomimicry

An iterative approach to solving problems in legged robotics is desirable because a continuous stream of minor errors can normalize to create a functional system. This is analogous to the natural process of evolution, where many generations of a specimen adapt over a period of time to "tune" themselves to changes in their environment. A legged robot is by definition "biologically inspired", meaning that living animals that share physiological qualities to it can provide highly optimized solutions for problems that it may encounter. If a researcher decides, for example, to build a robot modeled after a feline, then extensive documentation and "design" material already exists for examination, which could potentially minimize the chances of unnecessarily re-discovering effective solutions. There is a variety of different existing biological implementations of legged systems, so a prudent first step is to examine the main groups in expectation of locating one suitable for robotic biomimicry.

2.1.4 Types of Legged Systems

The number of ways to move on legs is equal to the number of different legged arrangements that exists multiplied by the number of gaits that each arrangement can have. Since the number of arrangements is theoretically infinite, systems will be distinguished only by the number of legs and the gaits that each type of system can have. This discussion will only present systems possessing between one and six legs.

Monopod

A monopod is a system with only one leg. To the knowledge of the authors, there are no land animals that rely on a single leg to move. However, several robotic devices exist that operate with a single leg.

Biped

A biped is a system with two legs. The most notable biological bipeds are humans. Bipedal lizards and mammals exist today, and a large number of identified species of dinosaur walked with two legs. Other examples of large bipeds are large fowl such as ostriches and emus. The highly "human" element of bipeds has made the bipedal arrangement an area of extensive research development and development in research laboratories worldwide.

Quadruped

A quadruped is a system with four legs. Quadrupeds are widespread throughout the Animal Kingdom, and include such animals as horses, dogs, cats, elephants, deer, bears, lizards, etc. Due to the large number of biological quadrupeds and other factors (discussed later in this chapter), quadrupeds are a very popular kinematic model for researchers.

Hexapod

A hexapod is a system with six legs. Hexapods are one of the most common types of creatures on Earth, as all insects have six legs. Hexapods have long been a popular arrangement in robotics due to their high-mobility, trivial control, and expandability.

Systems with eight legs (octopods) are another arrangement common in the natural world, however the characteristics and advantages for these are very similar to hexapods, so it will not be discussed separately.

2.1.5 System Characteristics by Number of Legs

Monopod

The gait of the monopod is limited; assuming that no other degrees of freedom exist other then the orientation of the leg with respect to the body, in addition to whatever degrees of freedom that the leg itself may posses, the gait is one where an impulse force is periodically created between the foot and the ground. Since the system does not have any additional legs to use for balance or change of stance during the aerial phase of motion, the force vector created at the time of lift-off must be oriented such that torques about the body are kept to a system-specific maximum. If this torque is exceeded, the body will pass its margin of stability on some axis and will be unable to prevent a fall. Since there is no static control option for monopods, the control system must be dynamic. However, this has been accomplished using simple Proportional-Derivative (PD) control loops. While not as practical as other legged systems, the single-legged quality makes monopods desirable for researching dynamic stability in the simplified case.

Biped

The number of gaits achievable by a biped is far greater than that of the monopod, even in the case of a simple, one-DoF per leg planar biped. The must well-known bipeds, humans, have an incredible number of different movement regimes possible, and are therefore considered a desirable arrangement for robotic systems. Assuming six DoF per leg, bipeds are kinematically dexterous and are therefore adaptable. Two is the minimum number of legs that a system can have and still posses static or quasi-static stability in addition to a dynamic gait. The system's center-of-mass can be cyclically exchanged from one support foot to another, resulting in a minimalistic yet efficient approach to locomotion. As stated in the introduction, stability is maintained if the systems center of mass (COM) is above and within the virtual support polygon defined by the area within the ground contact points. The support polygon will have the nominal area defined by the length of the foot portion in contact with the ground multiplied by the distance between each foot. The control of bipeds is highly non-trivial in both the static and dynamic case, which sometimes results in simplistic gait performance from otherwise very sophisticated research machines.

Quadruped

Quadrupeds are similarly as adaptable as bipeds. Four support points allow for static stability without compromising the dynamics of the system. Since the minimum number of legs required to achieve inter-phase control and stability is two, quadrupeds are capable of this while also possessing additional legs that can be used in tandem for faster, more stable gaits. The main types of quadruped gaits are: trotting, bounding, pronking, transverse gallop, and rotary gallop. In terms of stability, the two additional feet greatly expand the area of the support polygon (the distance between the feet that lie on the sagittal plane multiplied with the distance between those on the coronal plane), thereby allowing the center-of-mass a wider stability margin. The control systems for quadrupeds can range from simple behavior-based control to complex joint-trajectory planning algorithms.

Hexapod

Hexapods (and Octopods) have a redundant number of legs, and therefore are extremely stable and reliable walkers. However, this stability comes at the cost of speed and adaptability. Since the leg swing distance is fairly small with hexapods, many smaller steps must be taken to go the same distance. However, hexapods can be very efficient if actuated by non-back-drivable devices due to the weight of the system always being atop a three-contact-point support frame (i.e. the three legs in the static portion of the gait). Several different gaits are possible with many-legged robots, however most of them are some variation of exchanging support between pairs of three or more legs. Due to this simple requirement for stability, the control of multi-legged robots is usually far simpler than the control of quadrupeds, bipeds, and monopods.

2.1.6 Advantages of Quadrupeds for Research

Quadrupedal platforms have seen a high level of utilization in research and engineering for the following reasons:

1. Quadrupeds can be statically stable, simplifying control.
2. They are symmetrical about the sagittal plane, simplifying design and mathematical modeling.
3. Very high mobility can be achieved depending on joint arrangement.
4. Different gaits can be used to adapt to different locomotion scenarios.

Quadruped systems are more accessible because basic stability is immediately achievable with four static legs. If only one leg is moved at any given time (static gait), control is made relatively trivial; an exercises in static rather than dynamic systems. However, unlike hexapods, quadrupeds still have the potential to explore faster gaits by exploiting passive-dynamic properties. The variety of gaits available for investigation makes a four-legged robot a cost-effective platform for the general study of legged locomotion. Figure 2.1 below depicts several gaits that can be used for locomotion.

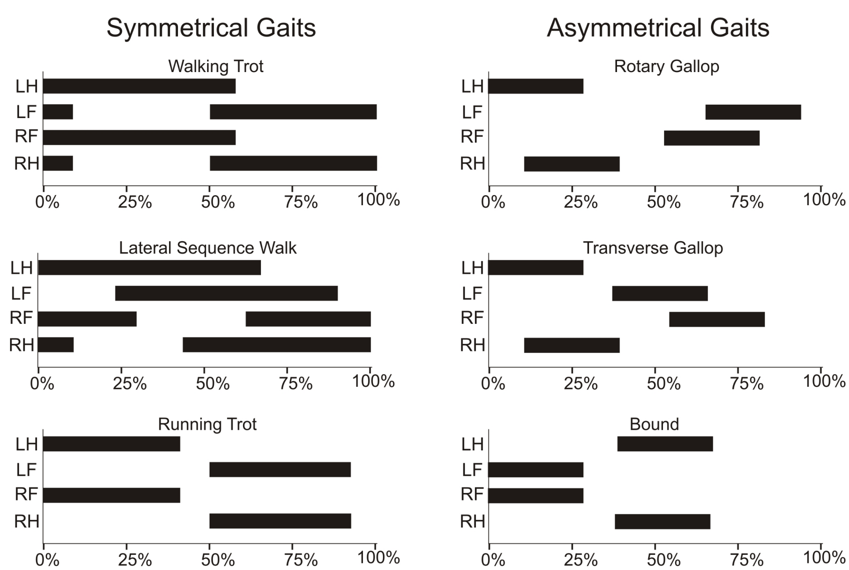


Figure 2.1: These plots depict the cycles of the four primary quadrupedal gaits.

In simple terms, quadrupeds have approximate the flexibility of bipeds while also approximating the stability of hexapods. Finally, new research into quadrupeds is practical since this area of robotics has already been explored to a large extent, and many important design and control lessons can be observed.

2.2 Current State of the Art

2.2.1 Existing Quadruped Robots

Many different groups around the world have conducted research into the creation of robotic quadrupeds. Many of these robots use simple static gaits, however since the authors are primarily interested in creating a robot with a dynamic gait, this kind will be discussed here more extensively.

At the MIT Leg Lab in 1984, Marc Raibert and collaborators created a simple, highly energetic and dynamic bounding gait quadruped. It was actuated by fluidic cylinders and partially relied on passive dynamic characteristics to achieve the desired motion. Gaits including bounding and trotting were achieved. (Raibert)

Figure 2.2: One example of a quadruped robot with a bounding gait.

Another quadruped was built at WPI by undergraduate students in 2011. The robot, ("Sabertooth") used electric motors and a cable-drive system for actuation. The design and manufacturing process for this robot was extensive, however to the authors' knowledge no functional control system was implemented. (Chernyak)

Figure 2.3: Sabertooth is a quadruped robot built at WPI.

2.2.2 Hydro-Muscles as an Actuator for Legged Robots

Hydro-muscles are a new type of soft, fluidic actuator with many applications in the field of robotics. A hydro-muscle consist of an elastic tube that expands when it is internally pressurized with a working fluid. When pressurized, the elastic stores energy in the form of elastic potential, which can be quickly released and turned into kinetic energy. The elastic tube is contained within a crumpled fabric sheath that has a diameter marginally larger than the outer diameter of the elastic tube. This fabric is fixed to the tube at both ends, and limits the muscle so it only expands longitudinally as it becomes pressurized (i.e. radial expansion is minimized).

The release of a pressurized hydro-muscle is very energetic. When the muscle is attached to a linkage, it can be kinematically modeled as a slider joint or as link with variable length. The muscle's rapid change in length can be used to do work. In this project, the team used the hydro-muscles to propel a quadrupedal skeleton by rapidly contracting each each of the skeleton's legs.

Hydro-muscles were invented in Popovic labs in 2013 by Dr. Marko Popovic. (McCarthy) During this time, Hydro-muscles were primarily used for proof-of-concept applications and were usually small with low pressures (i.e. less than 80 psi) to showcase the theory behind the technology. In the same year, a project advised by Dr. Popovic installed 3 hydro-muscles onto a model human skeleton arm to exhibit the muscle's capabilities. This arm can be seen in Figure 2.4.

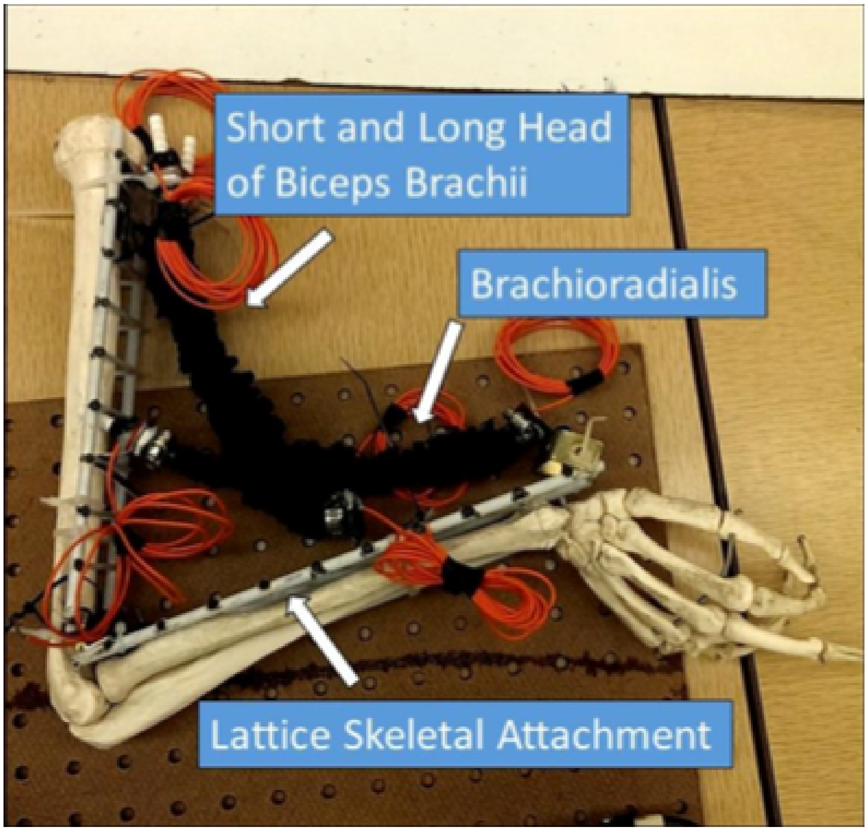


Figure 2.4: The skeleton arm was actuated by three separate hydro-muscles

Another research project which was undertaken by a separate group during the time of the quadrupeds development was the development of a system for fast, fine, position-control. This technology could be developed to build robot arms and legs that can perform very complex movements. These projects used muscles with 0.125" wall thickness and pressures between X and Y atm.

The robot described in this report required the development of hydro-muscles that are able to handle larger pressures and produce more power despite being subjected to external reaction forces on the order of 10kg. Our advancements in hydro-muscle building techniques are illustrated in detail in section 4.5. (change this)

2.2.3 Comparison of Actuators by Type

3 - Project Objectives

The main objectives that the team set out to fulfill were:

1. To develop a quadruped robot capable of a sustained bounding gait, with a fully aerial phase.

2. To demonstrate that hydro-muscles are suitable and reliable actuators for legged robots.

3. To construct a robotic platform for future research on leg kinematics to build on.

4. To further establish precedence at WPI for future projects in legged robotics.

3.1 Determination of Design Specifications

Prior to setting out to build a robot, the team established a series of specifications to set the bar for our own project's success. The following section illustrates the process and reasoning that let to the final project specifications.

3.1.1 Size and Weight

The team wanted to build a robot that was easily movable for testing in different locations, and for showcasing outside the WPI campus if such opportunities arose.

On the other hand the team decided the robot should be large enough so it is easy to work on, with standard hardware, piping components and tooling. Furthermore the robot should be large enough so that its actuation technology is appreciable. Children should be able to touch the skeleton and muscles without risk of damaging tot.

Based on these requirements, the robot should have a size on the same order of magnitude as a greyhound dog, with a weight no larger than 15 kilograms.

3.1.2 Cost

The HydroDog project had the objective to build a quadruped that is significantly less costly than other legged robot projects. High costs make legged robot projects highly inaccessible, and HydroDog aimed to take a stab at that.

Doing rough estimates of material costs the team calculated that the robot should cost less than $1,500 to build.

3.1.3 Actuation

Hydro-muscles have the distinct advantage of being capable of power augmentation; and if using an incompressible fluid, they have the potential for fine position control. Having invented these actuators, the faculty advisor felt that further developing the technology and testing it for different applications was a worthwhile endeavor.

The use of hydro-muscles to actuate the robot within specification and constraint inherent to the HydroDog project. The team embraced this constraint as a compelling challenge to do something that had never been done before.

3.1.4 Locomotion

Actuating each muscle requires two valves, one valve to allow fluid into the muscle(s) and one to open the muscle to atmospheric pressure. This means that actuating multiple degrees of freedom per leg would require more valves on board than our weight constraint permitted. A simple gait would facilitate the design and modification of the control system needed to actuate the muscles into a moving sequence. The team decided to attempt and develop a bounding gait because it can be modeled as a two dimensional system on the plane along the side of the robot. A bounding gait would also minimize the valves needed to actuate the system. Because the four legs can be actuated in pairs, the two front legs can be actuated with a single pair of valves, as well as the back legs.

3.1.5 Reconfigurability

Finding an ideal geometry for the robot's legs was a daunting task. The team performed extensive literary review on skeletal geometries of animals that run using a bounding gait, such as the cheetah and greyhound dog. The team also researched previous projects with legged robots to observe any existing trends in knee orientations, choice of joints for active versus passive actuation, and ratios for leg link lengths. Based on our research no apparent trend exists, with robot legs varying remarkably from project to project.

The team could not settle on an ideal leg ratio, leg size, knee orientation or resting leg position to use. Furthermore, the team could not predict how the system would behave compared to simulations with the same set of parameters.

To maximize our odds of finding a set of geometrical parameters that would produce a bounding gait with an aerial phase, the team decided to design a skeleton that is not bound to a specific geometry. Leg lengths and knee orientations should be variable, and components such as knee brackets and muscles should be easily interchangeable.

Reconfigurability and modularity would allow the team to very easily iterate between skeletal geometries in order to close in on a set of parameters optimal for forward motion.

3.1.6 Future Robotics Kinematics Platform

With such a vast project, the team was aware that a future team will pick up where we left off. The team decided that our robot should serve as a platform on which which future projects can build. Therefore, the project should be easy to understand and reproduce. Modularity and reconfigurability plays a major role into this specification because future teams should be able to attach more components and replace old ones with ease.

3.2 Project Scope and Limitations

The focus of this project was the design and implementation of a reconfigurable quadrupedal platform. There are several potential extensions to this project, however some of the more advanced functionality typically found in robotic system were determined to be out of the scope of this project. These limitations include, but are not limited to:

- Non-tactile exteroception (LIDAR, proximity sensing, etc.)
- Obstacle avoidance, mapping and navigation
- Fine position control of the hydro-muscles
- Teleoperation
- Advanced Simulation, Modeling, and Computational Optimization
- More than two actuated DoF per leg

- Directional Control of robot trajectory
- Custom-manufactured PCB components
- Advanced machining and fabrication techniques
- Separate control of each individual leg

It was established during the planning phase of the project that some of these topics may be explored if additional time was available following completion of the core project requirements.

4 - Design and Construction

4.1 Reconfigurable Construction System

In Section 3.2 it was determined that a reconfigurable construction system is critical for rapid physical design testing and iteration. This system not not only includes the primary structural components used to build the main chassis/skeleton of the robot, but also the mounting, attachment, adjustment, versatility which the resulting skeleton affords, as well as it's physical characteristics and logistics for appropriation and workmanship. To achieve this, the team initially built a 2-link test leg out of 1/2" aluminum square tube. Attachment holes were drilled with regular spacing (perforated) along each tube. Any attachment to a link could then be moved up and down by transferring it to the next mounting hole in line. While this prototype was interesting and featured more mounting freedom than a normal link, the manufacturing and reconfiguration processes involved were tedious and only allowed for discrete adjustment increments in the chosen hold-spacing increment. After further evaluation of this and other small prototypes, more comprehensive requirements were identified fore the robot's construction system. These are:

- **Modularity**: The structural elements of the system should be separable into a hierarchy of logical functional groups, such as link-leg-torso. The system should easily accept replacement, repair, and improvement to all structural components and groups of components.

- **Arbitrarily** Adjustable: Unlike the prototype leg, which could only be adjusted through a set of discrete configurations, the configuration of the elements of the construction system should be continuously adjustable into in infinitely many arbitrary configurations.

- **Rapidly Adjustable**: The research team should be able to easily and rapidly adjust the configuration of the components of the structural system, and doing so should require only standard hand tools.

- **Uniformity**: The system should be uniform and consistent throughout it's use in the robot.

- **Standard Interfaces**: The construction system should only use widely-available, industry-standard mechanical interfaces, such as fasteners, measurements, tolerances, etc.
- **Strength**: The primary purpose of the construction system is structural. The skeleton of the robot in particular must withstand the high forces, torques, and vibrations involved in quadrupedal bounding locomotion. The construction system must be suitably strong, stiff, and robust.
- **Affordable**: Any construction system that, when fully implemented, would put the project over-budget is useless. The system must be low-cost and in high availability.
- **Light Weight**: Similarly, the weight of the system must not over-constrain that of the other critical systems to comply with the total weight limit.

4.1.1 80/20™

After conducting research into commercially available construction systems, the team decided to invest in the 80/20(TM) Modular Framing, which consists extruded aluminium bar with a square profile featuring T-slots running along the length on each side, shown in Figure 4.5. 80/20™ extrusion, appropriately dubbed "The Industrial Erector Set"®, allows the user to quickly detach and reattach components, or to loosen their attachment, slide it along the bar, and re-tighten them at any point along its length.

Figure 4.5: 80/20^{TM} aluminum extrusion allows continuous attachment points along the slots.

The relevant advantages of T-Slotted framing are advertised by 80/20 Inc. as follows:

- No welding - no fighting heat stress or warpage
- Lightweight, easy to machine
- Uses standard fractional or metric fasteners
- Less engineering time required
- Easy to fabricate; only simple hand tools required
- T-slot technology is industry accepted
- No expansive fabricationg equipment required
- Easily reconfigured for design changes

These features closely align with the requirements of the robot's construction system, listed above. 80/20^{TM} is available in a variety of sizes, standards, profiles, and "series" of framing, each with a plethora of accessories. The 20mm square "20 series" was chosen for this application because it is the smallest profile available, and therefor the lightest. This framing is intended for the construction of load-bearing static structures, so it's strength still exceeds what may be required of the frame of the robot, but, as a result, is somewhat heavier than other aluminum construction systems of the similar profile size, such as the perforated hollow tube used in the first leg experiment. Furthermore, it's structural suitability in dynamic structures is not well demonstrated. However, the overwhelming 80/20$^{\text{TM}}$ suitability of the 80/20$^{\text{TM}}$ 20-series framing system according to the other criteria was deemed to outweigh these minor concerns.

The use of 80/20$^{\text{TM}}$ made iterating between leg geometries particularly easy because attachment points only had to be loosened, not detached, to be slid up or down links. Given the team's lack of easy access to computer aided machining facilities, 80/20$^{\text{TM}}$ provided a cheap and easy way to manufacture the skeleton.

The robot's body is a 80/20$^{\text{TM}}$ rectangle with two bars running lengthwise along the middle of it. Aluminum plates are attached on the inside and outside of the side-bars, and between each plate pair is the pivot joint between the body and a leg. The two bars running along the middle of the robot's body are used to attach the control system and most actuation components.

To attach pieces of 80/20$^{\text{TM}}$ together the team mainly used custom-cut pieces of medium density fiberboard (MDF). Manufacturing of MDF brackets and attachments plates was made fast and easy through laser cutting. These brackets hold 80/20$^{\text{TM}}$ rods at 90 degree angles at the corners of the robot's main body. MDF was used to mount the water pump on the robots body, and initially for main body plates and knee brackets. MDF Picture Here

All joints were hinges made with a hardened steel pin bound by bronze bushings on either side. Bushings made of SAE 863 Bronze (Oilite) were press-fitted into the brackets used for the hip and knee joints to minimize friction at the joints. Oilite is a porous bronze alloy impregnated with oil commonly used for low friction applications. The team fastened the steel pins with shaft collars on either side. Nylon washers were used as low-friction spacers to minimize contact between aluminum moving parts.

4.1.2 Skeleton Design

The design of the skeleton of the robot needs to facilitate adjustment of all major kinematic geometries while maintaining modularity, simplicity, light-weight, and structural rigidity. After simpler frames were tested, the final frame design was developed, shown below.

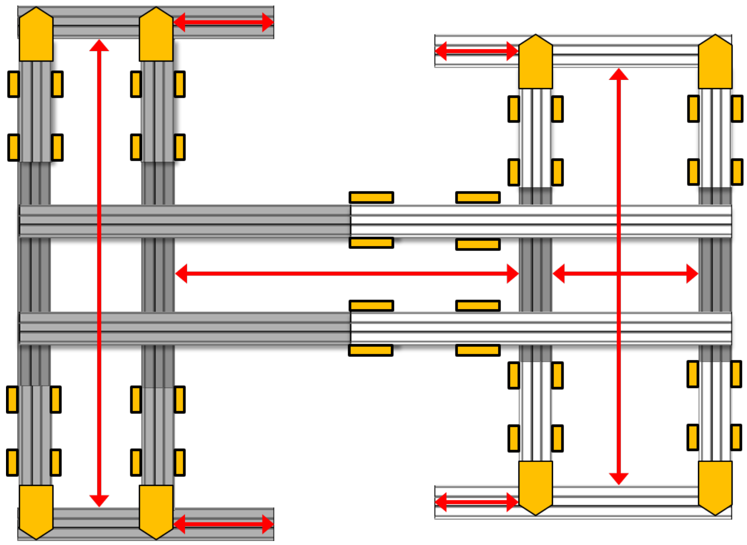


Figure 4.6: Top view of skeleton chassis.

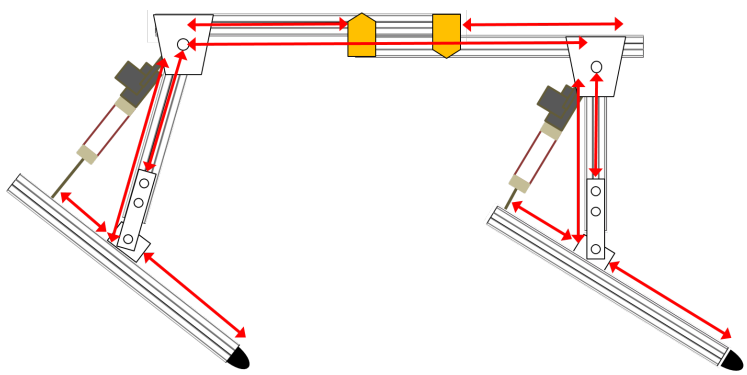


Figure 4.7: Side view of planar skeleton with muscles.

This frame allows for the easy adjustment of all leg link lengths and pivot points, muscle attachment points, body length, and the width of the front and back shoulders.

4.2 Modelling and Simulation

One of the goals of the HydroDog project is to develop a rapidly reconfigurable quadrupedal kinematic test platform. The primary advantage of rapid reconfigurability in a physical test platform is that the robot can be adjusted ”in the field” during testing, using human observation, analysis, and intuition to improve the kinematics. Another advantage, however, is that the robot can be rapidly reconfigured to match the configuration of a simulated quadruped model. The computer model can then be optimized computationally, and the resulting kinematic configuration quickly mirrored on the physical robot to test the accuracy of the simulated model. With an accurate simulated model and suitable optimization algorithms, the kinematics of the robot can be optimized even faster then rapid iteration on the hardware would allow. Thus, a computational model and simulation engine for the robot is highly desirable

The robot is symmetrical across the sagittal plane, and the left and right actuators are fluidicly linked as one actuated degree of freedom. Assuming the robot has a wide enough stance that sagittal stability is high, a planer model can capture all pertinent parameters of the kinematics, dynamics, and actuation. The sufficiency of 2 spacial dimensions greatly simplifies the model and simulation. As with all other aspects of the project, an off-the-shelf solution was preferred for these computational components. Research into 2D physics engines in which a complete dynamic model of the robot could be built and tested yielded two promising candidates: Box2D and WorkingModel2D.

Box2D is a popular and well-supported 2D physics engine. Although it is designed for 2D games, it has recently been used to optimize simple cars using genetic algorithms (see BoxCar2D). Because it is open-source and well-documented, it can be interfaced with optimization libraries, such as genetic algorithms. However, getting even simple kinematic and dynamic models working in this engine with realistic behaviors proved non-trivial. Furthermore, the optimization of these models using computational optimization algorithms - including genetic algorithms, simulated annealing, rapidly expanding random trees (RRTs), etc. - was attempted, but these efforts were eventually abandoned. Although interesting, such advanced modeling, simulation, and optimization is outside the scope of the current project.

WorkingModel2D is a commercial motion simulator for engineering. Thanks to a Graphical User Interface, functional and accurate kinematic and dynamic moving models can be quickly and easily created manually. Basic scripting capabilities are available using a Visual Basic-style built-in language, but cannot be interfaced with other software. Combined with limited documentation, proprietary licensing, this makes WorkingModel2D unsuitable for computational optimization of quadrupedal bounding gaits.

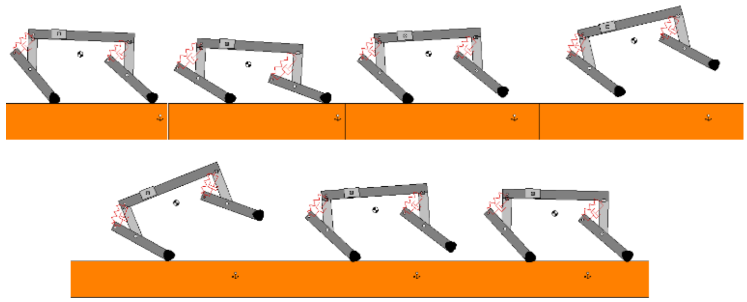


Figure 4.8: HydroDog Model in WorkingModel2D

4.3 Actuation System

Hydro-muscles are the only type of actuator used to actuate the robot. They are kinematically linked to drive the four legs to produce a forward gait. As described above, the basic hydro-muscle consists of an elastic tube constrained radially by a tightly-wrapped fabric sheath. It is usually plugged on one end with a barb, which is also used for mechanical attachment. A second barb on the other end serves as the other mechanical attachment point such that when the muscle contracts, it creates a tension force between these points. At least one of these barbs has an orifice that interfaces with the fluidic system, described below, to allow the elastic tube to inflate with fluid and deflate.

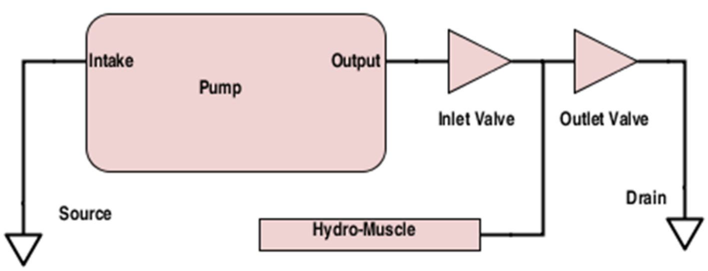


Figure 4.9: The basic structure of a Hydro-muscle pressure supply system

Hydro-muscles are a member of a larger class of actuators that operate using fluidic pressure and/or flow, known as fluidic actuators, “fluidic muscles”, “bionic muscles”, or “artificial muscles.” Almost all fluidic muscles, including hydro-muscles, have some common desirable characteristics. In general, fluidic muscles are:

Constructed using low-cost, safe, and widely available materials:

These materials normally include elastic tube, various types of fabric, webbing, or sheath, pneumatic or hydraulic fittings and fasteners, and water-tight adhesives.

Easy to fabricate:

They do not require machining or other advanced manufacturing processes and can usually be made in-house using basic tools and fabrication processes, such as sewing, press-fitting, coupling, screwing, gluing, tieing, and clamping.

Provide large contractile forces and fast movement:

Fluidic muscles are known for strong and fast linear one-way (pulling) actuation. Unlike other linear actuators - such as lead screws, timing belts, or hydraulic/pneumatic pistons - fluidic muscles can achieve both high-speeds and high-forces, resulting in smooth, powerful movements.

Easily mountable using two non-rigid attachment points:

Fluidic muscles - at-least those designed for the order of force under consideration for this robot - can be attached with simple cable ties or eye hooks. It is important to note that because the muscles pull on the attachment points, applying force along the line connecting them, and because rotation of the muscle about this axis does not usually affect its operation, the mounting scheme need not impose any further mechanical constraints on the muscle, and may hinder the operation of the muscle if they do.

Customizable:

Depending on their specific type and fabrication process, fluidic muscles can be made with continuously variable strength, length and/or extension. Furthermore, for any given type of muscle, the fabrication process remains virtually identical no matter the exact specifications of the muscles being made.

Mechanically and operationally simple:

Fluidic muscles do not involve complicated mechanism, electronics, or controls for basic operation. Their mechanical design is straightforward and in most cases their operation is well understood.

Robust:

Although they involve various kinds of material deformation, fluidic muscles do not involve parts sliding, or rotating or otherwise moving relative to each other. The lack of mechanical wear gives them exceptional reliability and life-spans. Furthermore, due to closed near-monolithic construction, fluidic muscles are well-suited for harsh environments and conditions, such as exposure to sand, dust, weather and extreme temperatures.

Central power source:

Perhaps the biggest advantage of fluidic muscles in general is their ability to be powered by a centralized fluidic pressure source. The overall system design is simplified because power transmission lines (fluid tubes) can also act as control lines (see controls section) . Furthermore, the consideration of different power requirements by different actuators then becomes a problem of power diversion through the fluidic transmission system (discussed below) rather than a choice of separate power sources tailored to the demands of every individual actuator. In addition, centralization implies higher efficiency. A single, large power source can be more efficient than many smaller power sources, because the ability to optimize increases with scale. For example, a single large hydraulic pump providing pressure to four fluidic muscles will usually be more efficient than four smaller separate pumps powering each muscle individually.

Hydo-muscles have all of these characteristics. However they also feature one more desirable advantage: inherent power augmentation, discussed below.

4.3.1 Power Augmentation

Hydro-muscles are unique among fluidic actuators because their power of actuation is supplied by the power source indirectly. Virtually all other fluidic actuators contract when pressurized and use this contraction as the direct actuation force. For example, this is the mode of operation of the most common and recognizable type of fluidic actuator, McKibben Muscles. When McKibben muscles are pressurized, they inflate in all directions, tending towards a spherical shape to maximize internal volume for their near-constant surface area (see Figure 4.10). This shape-change necessitates a contraction from their initial elongated state, and this contraction is utilized as the actuation force.

Figure 4.10: McKibben Muscle relaxed/unpressurized (Left) to contracted/pressurized (Right)

Although this force has the potential to be large and the resulting motion fairly high-speed, they are both entirely dependant on the fluid pressure and flow available from the pressure source during the time of actuation. In contrast, because hydro-muscles are constrained from radial expansion by their external sheath, the only method of volume increase is elongation, which is allowed because the fabric sheath can extend (increasing surface area). The muscle then behaves as a variable-length fluidic cylinder, where changes in internal fluid volume correspond to changes in length. As can be seen in Figure 4.11, while the walls maintain a constant diameter, internal pressure causes elongation (extension) by pushing outwards on the ends of the cylinder.

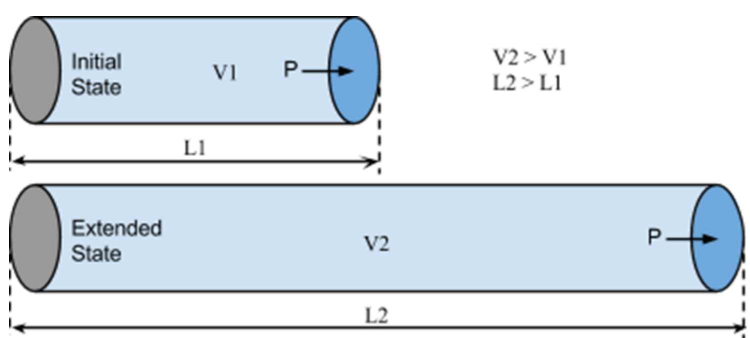


Figure 4.11: Hydro-muscle operation from relaxed/unpressurized (Top) to extended/pressurized (Bottom)

This pressurized extension is the distinctive behavior of hydro-muscles, however, it is only half of the functionality required for their inherent power-augmentation. The other functional requirement is elasticity. As the muscle extends, the elastomeric tube elongates. As with all springs, when the length is changed, the tube creates a force to return itself to its original state, and this force increases with the magnitude of the deformation (assuming the point plastic deformation is not reached). In the case of hydro-muscles, the tube provides a contracting force which opposes the extension force. Assuming no change in the fluidic pressure, the extension force remains constant while the return force increases with the extension length. An idealized mechanical abstraction of a generalized hydro-muscle is shown below in Figure 4.12. This model consists of a fluidic piston in parallel with an extension spring.

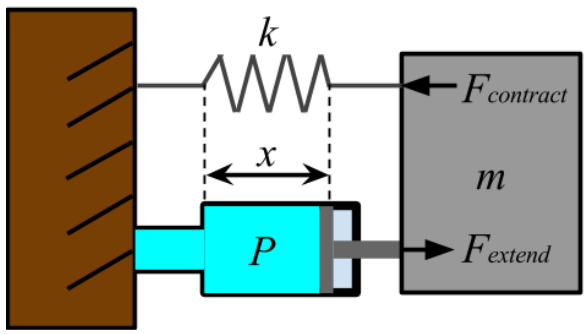


Figure 4.12: The mechanical model of hydro-muscle operation.

The muscles elongate until one of two states is reached: 1) the return force increases until it reaches equilibrium with the extension force or 2) the elongation limit of the fabric sheath is reached, constraining the maximum extension of the muscle and disallowing any further deformations. Depending on the application, either of these cases may be used.

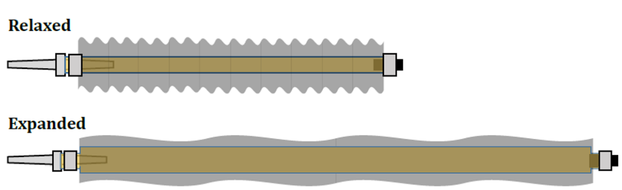


Figure 4.13: This drawing depicts the pressurization and extension of a hydro-muscle.

It is important that the elastic tube within the hydro-muscle possess ideal elastic properties (linearity, high spring constant), because it is the force of the elastic tube that causes contraction (actuation), not the pressure of the fluid as is the case in all other soft fluidic muscles. The fluidic power is mechanically decoupled and operationally distinct from the actuation power, hence there is no requirement that they be quantitatively related. Only the total energy involved is the same. As the muscle inflates, energy is stored elastically in the elastomeric tube. The maximum energy the tube can store is determined by the k value of the elastomeric material, it's cross sectional area, and it's maximum elongation when limited by the fabric sheath. When a hydro-muscle is extended, this energy can be stored indefinitely as long as fluid is not allowed to escape the muscle. When the muscle is actuated, the fluid is released, eliminating the extension force. The return force remains, and acts as the actuation force to contract the muscle.

Further physical analysis of this process is included below in section 4.4 - Fluidics. However, it is clear that through this inflate-store-release cycle, power augmentation is possible. Although the same amount of energy is involved in all stages, the amount of time each takes is independent. Therefore, energy can be put into the muscle relatively slowly (low power), stored for an arbitrary time, and released much faster (high power).† The power provided by the fluidic pressure source is automatically augmented by the inherent operation of the muscle. An analysis of hydro-muscle power augmentation is provided below in section 4.4.3 - Flow.

†Likewise, power diminution is also possible by quickly inflating the muscles and deflating them slowly. However, this mode of operation has little practical appeal for the current application of hydro-muscle technology as fast-contracting linear actuators. It may be useful for long-term energy storage and usage or fine position control in linear actuation.

4.3.2 Compliance and Incompressibility

One of the biggest desirable characteristics of fluidic muscles is the absence of mechanical rigidity and hydro-muscles share this advantage. Compliance is often regarded as an advantage for robotic actuation, especially in legged locomotion. Compliant legs are more adaptable to variations in terrain, more robust to perturbations, and can require less advanced control. (Someone sight Rob Full.) The compliance of a hydro-muscle is determined by the materials it is made of, the nature of its construction, the compressibility of the working fluid, and the features of the fluidic system to which it is connected. The use of more rigid materials, for example an elastomeric tube with a higher spring constant will increase rigidity. A more compressible working fluid will allow more deformation in the muscle, and thus more compliance and "springiness". Finally, if the working fluid is appreciably compressible, the more of this fluid that is contiguous (not separated by valves) with that in the muscle (the "extended muscle"), the higher the compressible volume, and the more compression and expansion will be allowed to transduce to the muscle. Therefore, an extensive contiguous fluidic system connected to the muscle will also reduce rigidity

It is assumed that all external forces acting on the muscle will put it in direct tension. This follows from the 2-point method of attachment, which, as described above, imposes the simplifying constraint that all forces act along the muscle's actuation axis. The mode of actuation is contraction, and this actuation should be applied to oppose external forces that will induce compliance. Therefore, the assumption that external forces should always put the muscle in tension is reasonable.

Hydro-muscles exhibit compliance only when they are partially extended. Barring mechanical failure, neither the application of additional internal pressure nor external force will further elongate a fully-extended hydro-muscle. For a partially-extended hydro-muscle, the extension force from the muscle's internal fluidic pressure is in equilibrium with the elastomeric tube's spring return force, and the muscle's length has not reached the limit of its external sheath. An external force pulling the ends of the muscle will tend to extend the muscle in a manner similar to its normal self-induced extension. The pulling force will act primarily against the spring force of the elastomeric tube, further extending the tube, while the sheath continues normal elongation. Assuming the amount of fluid in the extended-muscle is fixed, such externally-induced extension will also cause a vacuum pressure in the working fluid. If the fluid is compressible, it will compress, acting as another spring force in opposition to the external disturbance. If the working fluid is non-compressible, it will force the walls of the elastomeric tube to collapse inwards, decreasing it's cross-sectional area. (This happens to some extent with compressible fluids as well, depending on the compressibility of the elastomer in relation to the fluid.) However, both of these effects are expected to be small compared to the primary spring return force of the tube. This mode of compliance can be approximated using the parallel spring-piston model of hydro-muscles shown above.

4.3.3 Control

Control of fluidic muscles is often difficult because precise regulation of fluidic pressure and flow are not easily achievable without sophisticated and expensive valves. Even with fine fluid control, fine muscle position control does not necessarily follow because of non-linearities in the muscle dynamics. In general, position control of these type of linear actuators involves precise control over the volume of fluid in them, combined with an accurate physical model of the volume-to-position relationship for feedforward control and position sensing for feedback. In turn, velocity control involves command over the flowrate of the fluid into and out of the muscle (which in turn is adjusted by pressure regulation), combined with similarly advanced models, sensing, and feedback.

Hydro-muscles exhibit some theoretical advantages over similar fluidic muscles, namely their approximately-linear response in position to volume. The operation is similar to that of simple hydraulic cylinders, and therefore extension of the hydro-muscles is nearly proportional to to their internal volume of fluid. With constant input pressure, the final position of a muscle could be approximated for a given inflation time using the geometric properties of the muscle and the spring constant of the elastomeric tube material. Using the reverse calculation, the final extension of a muscle could then be controlled by inflating the muscle from a constant pressure source for a precise amount of time, either directly, or through constant pressure or flow regulation. In practice however, this kind of simple position control of hydro-muscles is non-trivial due to the effects of imperfections in muscle fabrication, non-linearities in the elasticity of the tube, the friction involved in the elongation of the sheath, and other discrepancies.

Nevertheless, such advanced control capabilities should not be necessary for the kinds of basic kinematic and gait tests the robot is intended for. For the purpose of ballistic control (Hosoda) testing, the robot's actuators need only be powerful, easily activated, and consistent. Hydro-muscles can be used in a way such that these properties are maintained. As described above, intermediate extension states are not controllable with a simple valve configuration, and therefore are not reliable under variations in fluidic pressure and external force. However, the completely relaxed state is consistent for a given hydro-muscle, as is the completely-extended state, regardless of the fluid pressure inside the muscle (for all pressures at or above that required to reach maximum extension). Furthermore, when non-compressible working fluids are used, the muscle contraction from the fully-extended state to the fully-relaxed state is also consistent (assuming that the pressure source is completely cut-off from the muscle during contraction, and that the muscle and it's exhaust are at a constant ambient atmospheric pressure.) For compressible fluids, different fluid pressures present at maximum inflation will result in different fluid densities in the muscle. The muscle's fully-extended internal volume remains constant, but the mass of the fluid in that volume will change, which will affect the contraction speed of the muscle when the fluid must be expelled. Although this behavior is undesirable, in practice, the variations in hydro-muscle performance using varying compressible fluid pressures - within a reasonable range - are negligible. This is because the mass of compressible fluids (gasses) are usually very small.

Since the contraction behavior of the hydro-muscles when they are operated at their extreme limits becomes nearly independent of inflation pressure, actuator control is greatly simplified. Precise timing and fluidic regulation is not needed to reach the extreme states. With a sufficient pressure source, the muscles can be inflated with any flow rate for any time longer than the inflation time, and it is guaranteed that the resulting muscle state will be fully extended. Similarly, the muscles can be exhausted with any flow rate for any time longer than the contraction time for that flow rate under the given load, and will end in their fully relaxed state. Larger loads (more opposing force or larger mass) will slow the muscle contraction in all cases.

With this method of operation, hydro-muscles are not only capable of power augmentation, but of power regulation/normalization. A fully-extended hydro-muscle represents a specific, constant amount of stored energy which which will be released in a (nearly) constant amount of time for a given load on the actuator.

4.3.4 Fabrication

Elastomeric Tube

The elastomeric tube is the primary component of a hydro-muscle's construction. As such, the choice of the material comprising the tube the its dimensions are the most important factors determining the functionality and behavior of the muscle. The primary purpose of the tube is to provide the contraction force of the hydro-muscle. Two factors contribute to this force: the spring constant of the tube (k), and the displacement length (ΔL) (extension) of the muscle when it is fully extended. The spring constant of the tube is a function of the total cross-sectional area (which in turn is a function if its internal and external diameters), and the Young's modulus of the material. The physical dimensions of interest for an elastomeric tube are shown in Figure 4.14.

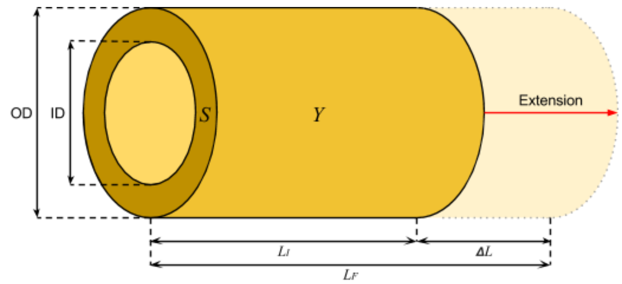


Figure 4.14: The physical parameters of an elastomeric tube.

$$S = \pi((\frac{OD}{2})^2 - (\frac{ID}{2})^2) \tag{4.1}$$

$$k = \frac{SY}{L} \tag{4.2}$$

$$F = k\Delta L \tag{4.3}$$

$$F = SY(\frac{\Delta L}{L}) \tag{4.4}$$

Increasing any of these factors - maximum extension, cross-sectional area, and Young's modulus - increases actuation force (roughly) proportionally, as does decreasing the initial length (L_I).

In addition to a high spring constant, it is also desirable that the elastomeric material have linear elasticity with small hysteresis, so that muscle performance is predictable and more accurately modeled as a simple spring. For these reasons, silicone tube is unsuitable. In difference, with near-linear elasticity, low hysteresis, and high spring constant, latex is an excellent choice, and latex tubing is readily available. The inner diameter of the tube should be chosen to interface with the standardizations used for fluidic system. Choosing a muscle ID smaller than that which is used in the fluidics system it is connected to restricts fluid flow, mitigating the optimization of the fluid system. Choosing a muscle tube ID that is larger than that used in the fluidics system makes muscle construction clumsy. For this reason, only $\frac{1}{2}$" ID latex tube was used to construct hydro-muscles for the robot. Since the inner diameter is therefore constrained to conform to the fluidics system, the only way to increase the cross-sectional area of the latex is to increase the outer diameter of the tube. To make the hydro-muscles as powerful as possible, the tube outer diameter should therefore be as large as possible. As such, the team procured latex tube with 1.125" OD, the largest tube with this inner diameter that was readily available from a common supplier.

(Latex tubes with these dimensions were actually not available. However, tubing with the correct inner diameter was procured ("small tube), along with tube of the largest possible outer diameter (large tube), and these were chosen such that the OD of the former matched the ID of the latter. Through careful manipulation and the application of various lubricants, the smaller tube was inserted into the larger tube, creating a conglomerate tube with the desired effective final geometry. No issues were encountered with this construction technique.)

Sheathing

The external sheath has three functions: it constrains the radial expansion of the tube, it allows for the longitudinal extension of the tube, and limits that extension to a maximum. To accomplish this, the sheath material must have a high tensile strength - in the transverse direction for radial constraint - and in the longitudinal direction for longitudinal constraint. Furthermore, it must have some method of extending longitudinally to some maximum limit, while maintaining a constant diameter. (Compare to McKibben Muscles, which have an external braided mesh sheath of a particular weave such that extension decreases the diameter. Extension without radial contraction is not possible with a weave alone.)

Two types of sheath designs were evaluated to achieve longitudinal extension of the sheath: "Uberhose" and "Crumpling".

Crumpled Fabric Crumpling sheath is the approach used for all previously demonstrated hydro-muscles. In this paradigm, a cylindrical sheath made of inextensible fabric is fabricated. The inner diameter of this sheath is slightly larger than the outer diameter of the elastomeric tube. The full, extended length of the fabric will be the maximum extension length of the muscle. To construct a muscle, this sheath is fitted around the un-extended elastomeric tube and crumpled on itself such that its entire length fits on the tube. The ends are then fastened as described in the next section. The crumpling does not significantly change the average ID of the fabric cylinder, so the cylinder can still fit around the elastomeric tube and act as a radial constraint during inflation. However, the sheath can extend in an accordion-like manner to its maximum length, when all of the crumpled ridges have been pulled taught. When the muscle contracts again, the fabric sheath naturally re-crumples to the "relaxed" state.

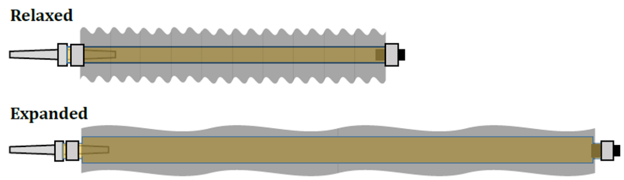


Figure 4.15: This drawing depicts the pressurization and extension of a hydro-muscle.

Suitable fabric cylinder sheaths designed for similar applications may be appropriated as a class of commercially available products, known as tubular webbing (Figure 4.16), usually made of nylon for high tensile strength. Common applications include climbing rope, harnesses and lashing, and in extensible garden hoses (the operation of these hoses resembles that of hydro-muscles, albeit for a different function.)

Figure 4.16: Nylon tubular webbing is an excellent sheathing material for hydro-muscles.

Tubular webbing comes in two common varieties: Edge-stitched and shuttle-loom. For Edge Stitching, a flat piece of webbing is folded over on itself and sewn together. Shuttle Loom is constructed by using one piece of "Thread" and weaving it on to a tube. Shuttle Loom is also known as the Spiral Weave and is preferred for hydro-muscles because the crumpling can be more uniform without the presence of a seam. Non-uniform crumpling results in non-uniform extension ("Corkscrewing") of the hydro-muscle. Although Shuttle-

Loom nylon tubular webbing is a near-ideal crumpled sheath, it was not available in sizes large enough to fit on this robot's latex tubes, and was therefore found to be an unsuitable sheath for this application of hydro-muscles.

Uber-Hose The other sheath paradigm, "uberhose", is named after the commercial product which inspired this approach and was used for all prototypes. Uberhose^{TM} (Figure 4.17) is the brandname for an expanding garden hose made by Guardenite. Like the tubular-webbing based garden hoses, its operation is again similar to hydro-muscles, however, uberhose features a smooth, flat expanded surface, instead of the crumpled surface.

Figure 4.17: The uber-hose sheathing is only longitudinally elastic, making it ideal for use with hydro-muscles

The Uberhose sheathing elongates in a fundamentally different way than crumpled fabric. Uberhose uses high-tensile strength thread in the transverse axis of its weave to constrain radial expansion, but elastic thread in the longitudinal direction. This elastic thread is incorporated with the non-elastic thread using special weave patterns, similar to those found in elastic waistbands. Like waistbands, uberhose can elongate elastically to a maximum extent, which is limited by the presence of non-elastic threads that become taught. Because of this construction, uberhose has two other important advantages over crumpled fabric for application as hydro-muscle sheath: elasticity, and a contracted relaxed state.

During operation as an actuator, the elasticity of the longitudinal threads of the uberhose augments the elasticity of the elastomeric tube it is surrounding, resulting in a muscle capable of generating higher forces. More force can be generated without modifying any parameters of the elastomeric tube discussed above because the uberhose acts as an adjunct to supplement the tube as well as a radial constraint sheath.

This elasticity also forces uberhose to contract by itself. Unlike crumpled fabric, which tends to uncrumple itself and elongate towards maximum extended length, uberhose's relaxed state corresponds to the relaxed state of the muscle. This behavior greatly simplifies the fabrication of hydro-muscles, because no tedious crumpling process is involved.

Unfortunately, despite these appealing properties, Uberhose™ has been found to be a unsuitable sheath solution for the muscles used in the robot because, like tubular webbing, it commercially available only in small diameter sizes. Uberhose™ is the only commercial product of its kind known to the authors, and this product is only available in one size - used for garden hose - which is too small to accommodate the thick latex tubes needed for the hydro-muscles used in this project. Prototypes and testing using Uberhose™ was therefore terminated early in the project.

Parachute Fabric Tubular webbing and Uberhose™ are both appealing off-the-shelf sheaths, but neither is available in large diametrical sizes. Fabrication of custom Uberhose-like sheath was quickly deemed unfeasible because the production method of these devices is outside of the capability afforded by the facilities at WPI. Therefore, custom crumpled sheaths were manufactured in-house and used in the final robot. Edge-stitch sewing was used because the loom machinery required to make shuttle-loom style was unavailable. Several generations of prototypes were constructed using different stitching and fabrics, most using canvas. However, these canvas sheaths ruptured when their muscles were inflated beyond 0.8 MPa.

Using a stronger fabric substitute - parachute nylon sheet - muscles sheaths were constructed that were never observed to fail mechanically under any conditions, which included pressures of above 1 MPa.

Barbs

Plugged End Cap To construct the end plugs of the muscle, the orifices of $\frac{1}{2}$" NPT nylon barb fittings were plugged with JB Waterweld™ epoxy. Steel "eye" hooks were embedded in this epoxy to provide a mechanical mounting/attachment point at the end of the muscle.

Open End Cap Custom open barb ends were fabricated using 3D printing techniques in polylactic acid (PLA). Male $\frac{1}{2}$" NPT Nylon barbs were connected to both ends of these parts using JB Weld^{TM}, forming an angled fitting to connect the muscle to the fluidic system, while also providing a mechanical attachment point. This assembly is shown in Figure 4.18 below. These parts were designed such that the mechanical attachment is directly in-line with the central axis of the muscle, and fluid is directed around this attachment by a small angle to minimize fluidic drag.

Figure 4.18: The 3D printed components served as fluid inlets as well as mechanical attachment points for the hydro-muscles.

These fittings were suitable for testing hydro-muscles under low pressures, however small leaks became visible under higher pressures (0.7 MPa), and these leaks remained even after attempted repairs with leak-fixing epoxies. Several techniques were attempted to remedy the issue, but eventually new fittings were proposed and assembled using off-the-shelf NPT fittings. These fittings consisting of a $\frac{1}{2}$" NPT barb on one end of a T-junction to interface with the hydro-muscle, a plug with eye-hook on the other end, and a $\frac{1}{2}$" NPT barb in the middle of the T-junction to interface with the fluidic system. Although these assemblies were bulkier than the custom parts they replaced, and the right angle fluid junction is non-optimal for flow, they proved to be completely reliable under extensive testing with the robot, both mechanically and fluidically. Pressures in excess of 1.2 MPa were tested without incident.

End Fastening and Attachment

The high internal pressure of the hydro-muscle's latex tube applied to the $\frac{1}{2}$" diameter plug creates considerable force pushing the plug out of the tube (popping). Under 1 MPa (150 psi) pressurization, this force is:

$$Force = (Pressure)x(Area) \tag{4.5}$$

Substituting:

$$Force = 150\pi(0.25^2) = \ 30lbf \tag{4.6}$$

Furthermore, when acting as actuators, there are large external tension forces acting to pull the components of the hydro-muscle apart. As such, the plugs pulling free of the clamps was the most common mode of failure encountered while testing hydro-muscles. The most basic and common method of capping the hydro-muscle is to insert barbed connectors into the ends of the muscle, then clamp ends of the sheath and latex tube tightly around the barbs with hose-clamps. However, this approach was found to fail at pressures exceeding 0.9 MPa or vigorous actuation at lower pressures. Two modifications were made to this construction: First, the latex tube was adhered directly to the nylon barbs using cyanoacrylate adhesive. Second, the hose clamps were tied directly to the end caps using galvanized steel wire.

4.3.5 Final Construction

When combined, these design choices and construction techniques - large latex tube, nylon fittings, parachute fabric sheaths, and glued/clamped/tied endcaps - were used to fabricate robust and reliable hydro-muscles that did not fail during the final stages of testing. An image depicting the hydro-muscle's final construction method is shown below in Figure 4.19 and Figure 4.20.

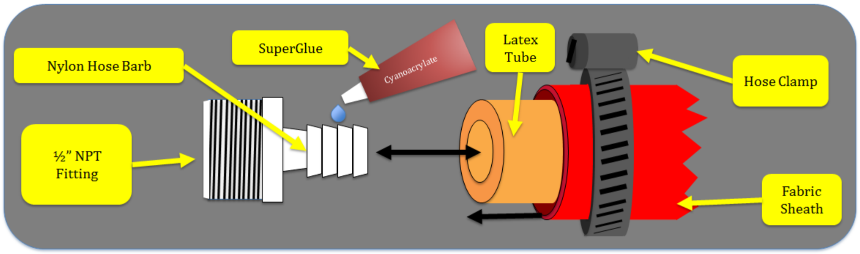


Figure 4.19: The use of adhesive, parachute fabric, and hose-clamps results in a robust muscle.

Figure 4.20: The hydro-muscle that was used for the final iteration.

4.3.6 Evaluation and Verification

Because the hydro-muscles used for this project used significantly different construction techniques and materials from any that had been previously demonstrated, it was neccesary to test the agreement between the hydro-muscle theoretical model and their operation in practice. To do this, a demonstrative hydro-muslce was constructed and inflated to different pressures between 0 and 100psi. The length of extension was recorded for each pressure, and the muscle was discharged into a graduated cylinder, with the volume added to the cylender taken as the volumetric change in the muscle between the extended state and its relaxed state. The results of these tests are shown below.

TEST	Pressure (psi)	Length (in)	Volume (mL)
6	58	12.25	115
8	60	12.25	80
4	60	12.6	120
5	65	13.75	140
3	67	14.25	160
1	70	14.75	170
2	76	15.5	180
7	90	16	200

Table 4.1: The extension length and internal volumetric displacement of a Hydro-muscle inflated with different pressures.

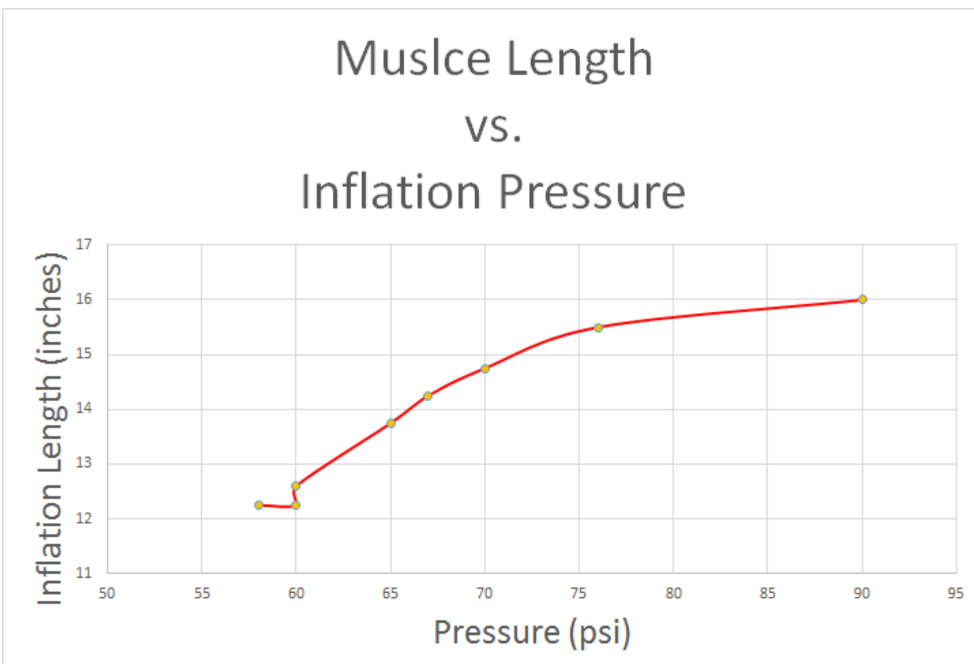


Figure 4.21: Hydro-muscle Inflation Pressure vs. Extension Length

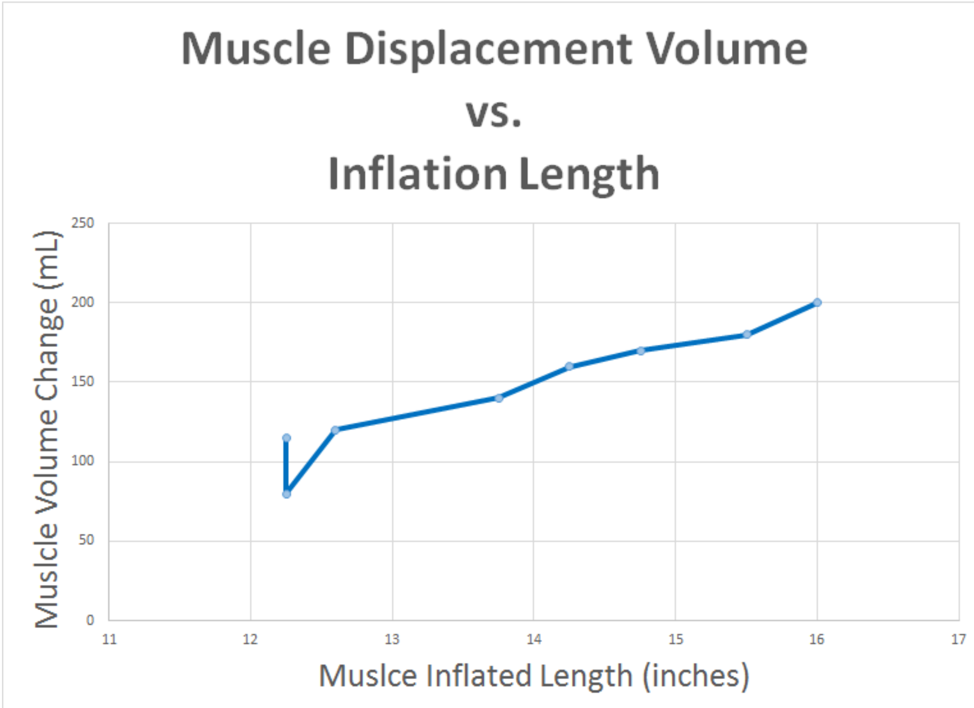


Figure 4.22: Hydro-muscle Inflation Length vs. Volumetric Displacement

Based on the results of these tests, the relationship between internal inflation pressure and extension length, and between extension length and volumetric displacement, were both found to be roughly linear (proportional), as expected. This confirms the fluidic-cylinder model of hydro-muscle extension, and shows that the construction methods and materials used for the muscle do not adversly effect it's predictable behavior as a linear actuator.

4.3.7 Parallel Operation

The power of hydro-muscles is practically limited by the sizes of their constituent components. Larger, more powerful hydro-muscles could not be readily constructed because larger latex tube was unavailable.

In anticipation for the need for greater actuation power, another approach was explored instead: operating multiple hydro-muscles in-parallel. In this configuration, two or more hydro-muscles may be connected fluidically and attached to act together mechanically. One theoretical advantages to this approach is to achieve greater actuation power using the same fluidic pressure and without requiring a greater fluidic flow-rate.

For example, a single hydro-muscle may be replaced with two smaller hydro-muscles used in parallel with each other. If the geometries of these smaller muscles are chosen such that they have a greater combined cross-sectional latex tube area than the larger muscle, then they will have a higher force and contract more powerfully. (They must have the same contracted and extended lengths as the original so that their behavior as actuators is mechanically equivalent). Furthermore, because they have smaller diameters†, even combined, they will have have less internal volume, and therefore need to move less fluid when actuating. Less flow during inflation lessens the demand on the fluidic pressure source, and less fluid displaced during contraction means less fluid mass to accelerate, giving faster acceleration and faster-contraction (more powerful actuation).

†Smaller diameter muscles tend to require higher pressures to fully extend. This analysis assumes a pressure which is sufficient to inflate all muscles under discussion to their maximum extension limit, as described above in 4.3.4 - Elastomeric Tube.

However, the considerable inefficiencies arise due to the nature of the fluidics system needed to operate two muscles in parallel, and additional complexity arises in the construction and attachment. In practice, these factors proved to negate the advantage of their additional theoretical power.

Dual-muscles were constructed, as shown in Figure 4.23. They were made by coupling a piping-T with two "L shaped $\frac{1}{2}$" NPT-to-barb" plastic fittings. These fittings were hose-clamped to the latex tubes, which were in turn plugged at the other ends and joined by a steel rod.

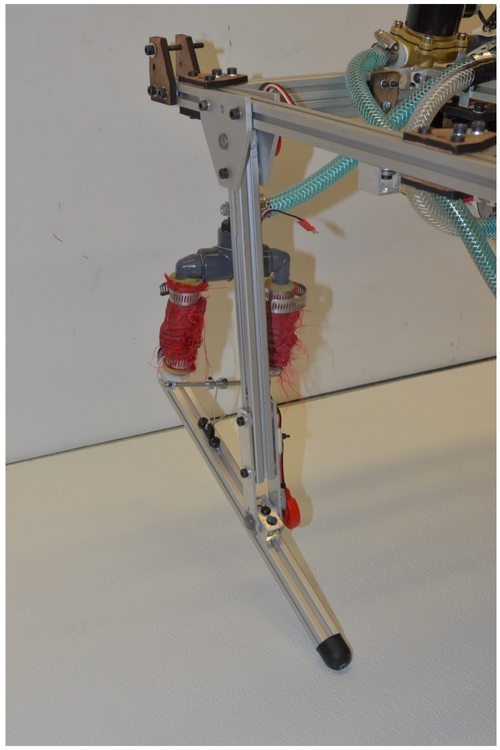


Figure 4.23: Two muscles were placed on each rear leg in an attempt to increase the force.

4.4 Fluidic System (Power Transmission)

The fluidic system effectively acts as the power transmission for the robot. It is responsible for distributing, controlling, and regulating fluid pressure and flow between the pressure source (pump), the hydro-muscles (actuators), and a fluid pressure drain (exhaust). A basic fluidic system routes fluid from the fluid source to the intake of the pump, from the output of the pump, through inflation control valves, to the hydro-muscles, and from the hydro-muscles, through deflation control valves, to some fluidic pressure drain/dump. This drain may be the external atmosphere for open pneumatic systems, or some liquid reservoir for hydraulic systems. In either case, the drain's primary feature is that it is at a lower pressure than the rest of the system and is capable of accepting the fluid discharged by the system. Figure 4.9 depicts this type of system in its most basic form.

There are four primary considerations for the fluidic system: Pressure, Flow, Weight and Standardization. These are explored here.

4.4.1 Pressure

The safety, reliability, and performance of the fluidic system require that all pressurized portions of the system be rated at or above the maximum operating pressure of the robot. From the physical analysis of hydro muscle operation, detailed in Chapter 4 - Actuation System, the system should operate at a pressure of at least 100 psi to provide reasonable muscle extension lengths and forces at those lengths. To provide a safety margin while staying within the common maximum pressures for the standards chosen in the next section, it was decided that all components of the system should be rated for at least 150 psi.

4.4.2 Flow

The efficiency of the fluidic system as a power transmission is determined by the way fluid flows through the system. Several general guidelines are derived below for the design of an efficient fluidic system for hydro muscle actuation.

The hydro-muscle actuators achieve power augmentation by storing energy over a period of time and releasing that energy over a shorter period of time. Both the inflation (extension) phase and exhaust (contraction) phase of operation are important to the efficient operation of the robot overall. However, while robot locomotion will be hindered by slow or inefficient muscle inflation, it will be impossible (for the locomotion scheme investigated in this report) without powerful contraction. This is why power augmentation is a desirable property of hydro-muscles as fluidic linear actuators; the fluid pump does not need to supply the instantaneous flow or pressure required during actuation. Since the robot's locomotion depends more upon powerful contraction than on fast extension, preference is given to optimizing these portions of the fluidic system. This is the first guideline for the design of the fluidic system: priority should be given to the optimization the flow-rate of exhaust before any other portion of the system.

Efficient operation of the hydro-muscles requires that minimal power from the pump is lost while inflating them, and, more importantly as per the above guideline - that they be able to deliver their stored energy as fast as possible (powerful actuation). The fluidic system should accommodate rapid fluid acceleration and movement both to and from the hydro-muscles, with much higher importance placed on the latter (exhaust.) A simple physical analysis of the exhaust phase of the hydro-muscles gives two more fluidic system design guidelines, derived below:

When the muscles are inflated, the latex tubes act as springs which store elastic potential energy as they are extended. When the muscles are deflated, these "springs" exert a contraction force, with an initial value F_i. This force is applied over the time that the muscles are deflating, t_C, in which the muscle contracts in length by a distance Δx. The force decreases linearly with the muscle's extension relative to its relaxed length (x=0) according to Hook's law:

$$F = -kx \tag{4.7}$$

The muscle will stop contracting, with a final force F_f, for one of two reasons: 1) the muscle has reached its relaxed state and the elastic tube "springs" are at zero extension (x=0), producing no further contractile force or 2) an external limit is imposed on the contraction of the muscle, such as a kinematic limit to its minimum length† or the closing of its exhaust passage. In this case, the muscle may end in a "pre-tensioned" state (x≠0) and the final force may not be zero. In either case, the total work done by the muscle is equal to the average of the final and initial forces, multiplied by the distance over which the force was applied, as seen in Equation 4.8.

$$Work = \Delta x \frac{(F_I + F_F)}{2} \tag{4.8}$$

This work is numerically equal to the change in the potential energy that it stored.

$$Work = \Delta P = \frac{1}{2} k (x_I^2 - x_F^2) \tag{4.9}$$

The work of the muscle is done on two bodies: the robot M_R, (through leg kinematics) and the fluid M_F, contained in the tubes directing fluid from the end of the muscle to the exhaust. The purpose of the muscles is to move the robot, so it is desirable that as much of this work be applied to the robot as possible, instead of the fluid. The result of work is a change in kinetic velocity (acceleration), therefore the fluidic system should be designed to minimize the change in kinetic energy of the fluid between the muscle and the exhaust as the muscles are contracting. Assuming that the fluid has zero initial velocity, it also has zero initial kinetic energy, and this reduces to minimizing the final kinetic energy of the exhaust fluid.

$$\Delta K = K_F - K_I \rightarrow K_I = 0 \rightarrow \Delta K = K_F \tag{4.10}$$

The kinetic energy of a body is proportional to its mass and velocity.

$$K = \frac{1}{2}mv^2 \tag{4.11}$$

The fluidic system is modeled as a series of tubes. One way to minimize the kinetic energy of a fluid moving through a tube is to reduce its mass. The mass of the fluid is the product of the density of the fluid and the volume of the tube.

$$M = \rho V \tag{4.12}$$

Assuming that the tubes are cylindrical, then the mass of the fluid is given by Equation 4.13, where ρ is the fluid density, r is inner radius of the tube, and L is the length of the tube.

$$M = \rho \pi r^2 L \tag{4.13}$$

Without modification to the universal constant π, volume minimization can therefore be accomplished in only two ways: 1) reduce the length of the tube, L, or 2) reduce the radius of the tube, $d = 2r$. Other considerations aside, the former method - minimization of the length of the exhaust tubes - becomes the first objective for the design of the fluidic system: tubes should be as short as possible to reduce fluid mass (i.e. only long enough to reach directly to the points of actuation).

However, a trade-off is encountered in the consideration of the latter method: reduction of tube diameter. For a given muscle undergoing a given change in length (contraction), it's change in fluidic volume is constant. This exhaust fluid volume change V_E must therefore be transferred through the exhaust tube within the muscle's contraction time via fluid flow. When the diameter of a tube is reduced, its cross-sectional area is reduced, so fluid velocity must increase to maintain the same net flow rate as seen in Equation 4.14.

$$Flow = \pi r^2 v \tag{4.14}$$

As concluded above, the fluidic system should be designed to minimize the kinetic energy of the exhaust fluid. This kinetic energy is proportional to the mass of the fluid (which is proportional to the tube's diameter), and also to the square of its velocity (which increases as the square of the fluid velocity, which in turn is inversely proportional to the square if its diameter.) This means that there is a net increase in fluid kinetic energy from a reduction in tube diameter. For example, halving the diameter of the tube will reduce the mass of the fluid by a factor of four, but will also increase the velocity by four times, resulting in a net four times increase in kinetic energy - and four times more work - to move the same volume of fluid through the tube in the same time period.

Maximization of the diameter of the tubes is then the second general guideline for the design of a fluidic system for use with hydro-muscles: Tubes should be as wide as possible to minimize fluid velocity. However, other considerations, namely standardization and weight, will limit the maximum practical tube diameter. With these considerations, discussed below, an internal diameter of $\frac{1}{2}$" was used and found to be sufficient for most regions of operation of the robot.

†Due to the methods by which the muscles are constructed, when a muscle's contraction is limited by an external length constraint, but not fluidically, it may continue to expel fluid due to minor residual inflation (but not extension) in the latex tube within its sheath. Although this discharge represents wasted fluidic work (which is an inefficiency in the overall operation of the actuators), it does not affect the work that the muscles do during their main "useful" contraction phase, and therefore is ignored in this section, which pertains to the optimization of that contraction through fluidic design.

4.4.3 Standardization

To allow for rapid construction, adjustment, reconfiguration, and repair, all components of the fluidic system should be of the same standardized size and uniform throughout the system. There are several common standards for hydraulic and pneumatic systems, namely National (American) Pipe Thread Tapered (NPT), British Standard Pipe Thread (British Standard Thread), and Male Iron Pipe (MIP). Of these, NPT was selected because NPT components and fittings are readily stocked by local suppliers, and critical components - including the pump and valves - are also available with NPT fittings.

4.4.4 Weight

The improper choice of fluidic system components can incur a severe weight addition to the robot. As with all other systems, the fluidic system had to be as light-weight as possible while still satisfying its other requirements. Fluidic components are most commonly available in two classes of materials: metals - such as brass, copper, and stainless steel - and plastics - such as nylon, polyurethane, and Polyvinyl-Chloride (PVC). Although the metal components are stronger and rated for much higher pressures, they are also significantly heavier, usually on the order of five times. In most cases, plastic components were available with sufficient pressure ratings and were therefore selected. In particular, nylon components were favored for their light weight, rigidity, and machinability.

Based on these four requirements, a standardized fluidic system was designed consisting of $\frac{1}{2}$" NPT nylon fittings connected with high-pressure, highly-flexible $\frac{1}{2}$ ID polyurethane tubes. The physical layout of the system on the robot, shown below in Figure 4.24, was chosen to minimize the distance between the hydro-muscles and their respective exhaust valves, and between the exhaust valves and the reservoir.

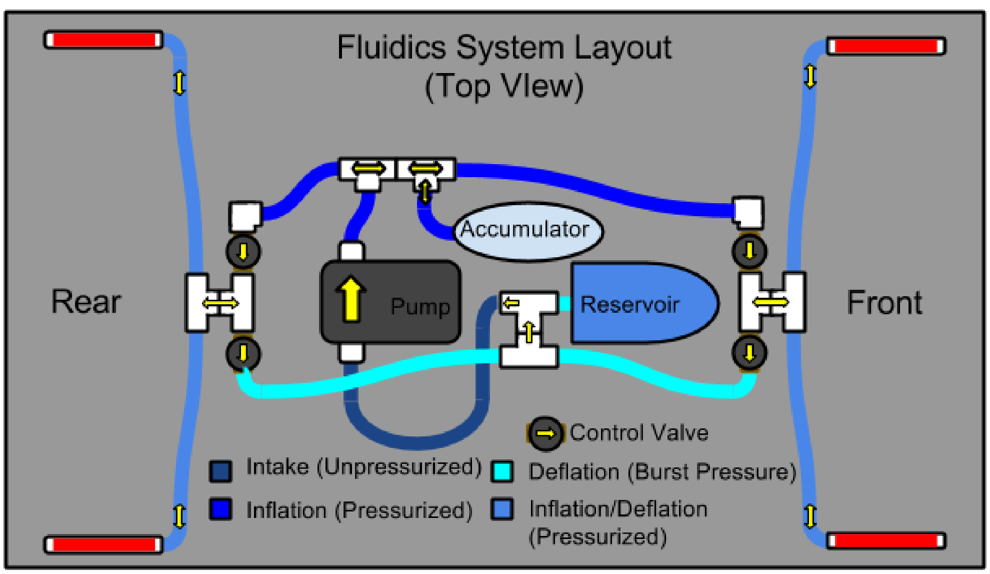


Figure 4.24: A diagram depicting the design and layout of the robot's fluidic system

4.4.5 Accumulator

Despite their inherent power augmentation effect, hydro-muscles still require a considerable net fluid flow and pressure input to actuate in the manner required for dynamic legged motion. Depending on the size and volume of the muscles and frequency of their actuation, commercially available hydraulic pumps may still be incapable of providing this flow-rate at the required pressure. Furthermore, the pressure and flow (fluidic power) provided by the pump is only needed intermittently. During ideal normal operation, the pump is activated to inflate the muscles, but deactivated for the short time they are deflating,as it would be counterproductive to let the pump inflate the muscles at the same time that they were deflating. A pressure/volumetric accumulator is therefore desirable for two reasons: 1) for macro power augmentation and 2) as a fluidic "capacitor" to smooth the pressure and flow demands on the pump. A robot possessing macro power augmentation via the accumulator is able to store energy in the form of a volume of pressurized fluid. It "charges" the accumulator while stationary, or while using a slower, less demanding gait. The robot may then use that large store of energy for quick "bursts" of operation using a fast gait ("sprint") that the pump would be unable to power directly. The micro power augmentation of the individual hydro-muscles is still in effect, but a much larger volume of pressurized fluid is available to inflate the muscles more rapidly. Inflation takes longer than deflation, so its reduction allows for much faster overall gaits, even if these gaits can only be sustained for short periods as determined by the energy capacity of the accumulator. This mode of cyclic "charge-burst-charge" or "rest-sprint-rest" operation also allows the pump to run for longer periods of continuous operation. Meanwhile, during the "sprint" phase, the pump can supplement the stored energy of the accumulator. In this case the pump can run continuously even though the demand of the muscles is intermittent, because its power can be directed to charge the accumulator. Hence, the addition of an accumulator can increase the power of the robot as a whole, because the pump in an inactive state. During sustained gaits that do not require macro power augmentation, the stored energy in the accumulator supplements the power of the pump. It is also noted that, in practice, hydraulic pumps have non-negligible start-up time, whereas the the response time of an accumulator is near-instantaneous. The accumulator therefore provides another small efficiency gain by damping or eliminating impulse pressure requirements.

The choice of an accumulator involves a trade-off between performance and run-time.

A larger accumulator can store more energy and therefore provide longer sprints, but will also be bulkier and heavier (especially when filled with hydraulic fluid).

As mentioned earlier, the function of the accumulator in a fluidic system is analogous to a capacitor in an electrical system. As with capacitors, the pressure (analogous to voltage) of most simple accumulators will decrease as they are discharged. However, it is feasible to construct constant-pressure accumulators. One approach is to push an open-ended hydraulic piston with a constant-force spring. Another is based on a pneumatic piston with variable-sized plunger (Van de Ven) (See Figure 4.25.

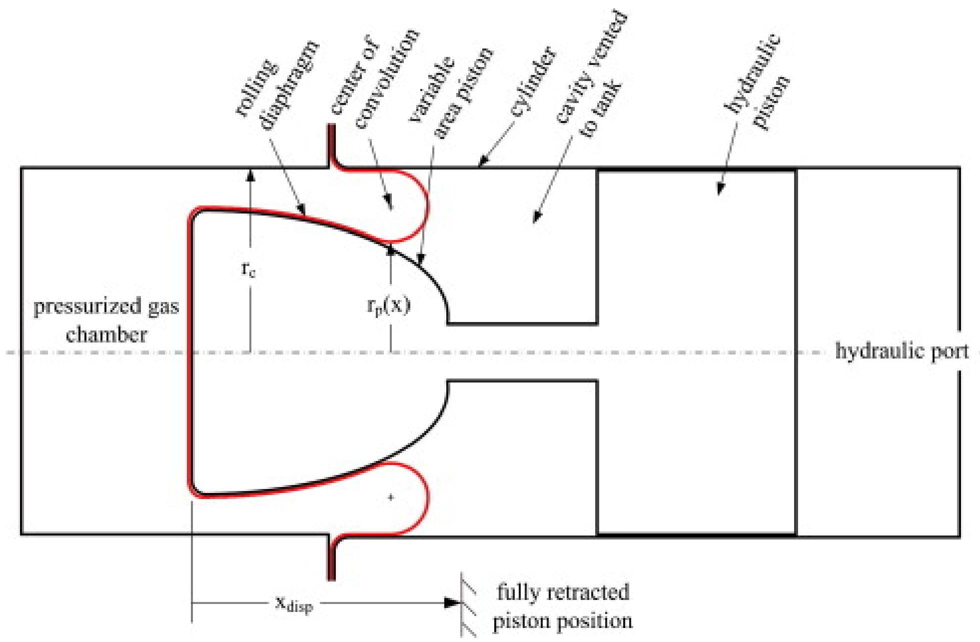


Figure 4.25: A conceptual diagram of a constant-pressure accumulator

4.4.6 Reservoir

For a closed-loop hydraulic system, a reservoir is needed as the supply for the pump intake, a repository/store for extra fluid, and a receptacle for fluid exhaust from the muscles. The primary feature of this container is that it can act as a receptacle for a varying volume of fluid, but is not pressurized.† Because it is not pressurized, the reservoir can be open to the external atmosphere. However, in practice it is desirable that the hydraulic fluid be separated from air to prevent contamination and aeration. In particular, an inelastic, flexible membrane "pouch" with sufficient maximum volume is an ideal closed container capable of passively varying its volume.

Initial custom prototypes of this “pouch” failed during testing, so an off-the-shelf solution was sought. After reviewing commonly available commercial products designed for similar functionality, a suitable solution was found in the portable hands-free personal hydration space: CamelBak’s^{TM} Antidote®Lumbar 3L Reservoir, shown below in Figure 4.26.

Figure 4.26: The CamelBak flexible fluid reservoir was chosen for its strength and low-weight.

The cap of the Camelbak was modified to interface with the rest of the hydraulics system. This involved drilling holes in the original cap and connecting $\frac{1}{2}$” NPT female fittings to the holes using JB WaterWeld^{TM} epoxy putty.

4.4.7 Hydraulic

Hydraulic systems are defined by the use of non-compressible working fluids. Industrial hydraulic systems often use specialized hydraulic oils, which are designed to be non-compressible under extremely high pressures, withstand high temperatures, and/or perform other auxiliary functions such as lubrication. However, none of these capabilities were required for the present hydraulic system, and such oils are usually expensive, flammable, toxic, or otherwise impractical. Water was chosen as the hydraulic fluid because it is easily obtainable at almost no cost, non-toxic, and easily cleanable. Purified, deionized water ("DI water") was used instead of tap water to reduce contaminants, particulates, the potential for bacterial growth and the corrosion of certain parts of the fluidic system, including the valves and pump.

The DI water was stained with culinary gelatinous dye (food coloring) to make leaks in the system more noticeable and assessable, and to increase the visibility of air bubbles in the transparent vinyl tubes, which is important for the purging process described in Section 5.1. The color blue was chosen for consistency with the aesthetics of the rest of the robot. This coloring had the unintended side-effect of endowing the researchers with a Smurf™-like guise following direct observation of catastrophic failure during high-pressure hydraulic tests.

4.5 Dynamics

The team designed HydroDog's skeleton so that its legs would launch it off the ground and in a forward direction. In order to do that, the team tested two ways to actuate the legs: Hip/shoulder actuation, and knee actuation. Hip and shoulder actuation gave the muscles too small a moment arm on the leg compared to that of the floor. This approach was quickly given up on and muscles were placed in the robot's knees. A skeletal iteration with muscles actuating hips and shoulders is shown on Figure 4.27.

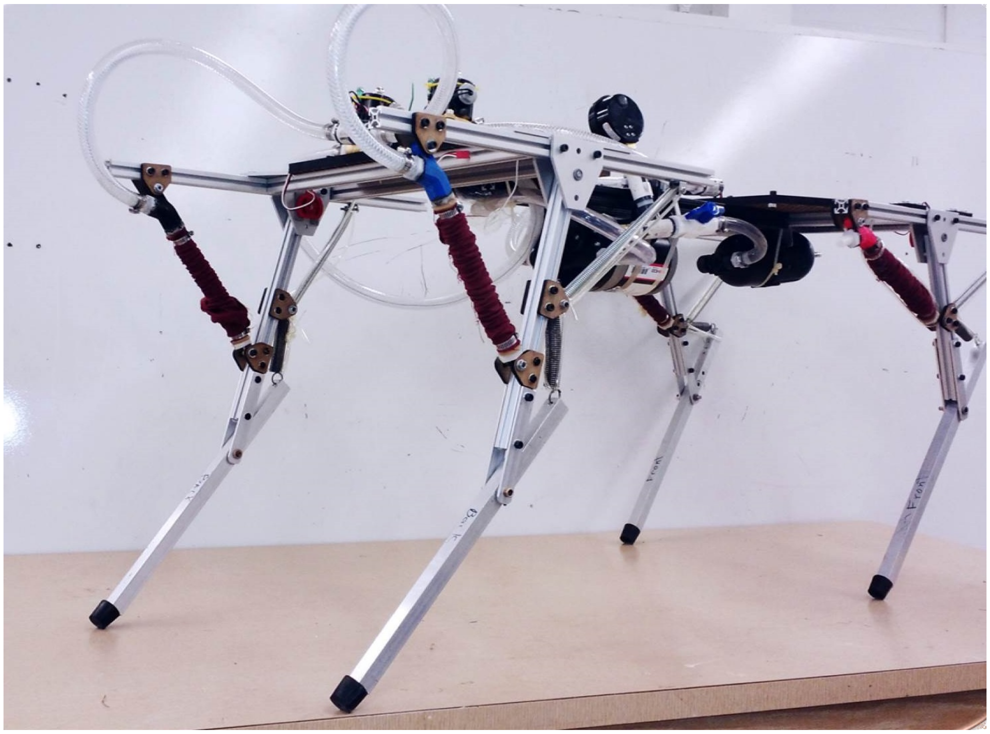


Figure 4.27: A previous iteration of HydroDog with actuation at the hips and passive elastic knee joints.

The team attached the muscles on the points that would create both the passive stance of the robot and the final launch position during actuation. The front legs should provide more lift than forward force. By pushing straight up a distance from the center of mass, the front legs create more rotation than translation.

On the other hand, the rear legs have a line of action much closer to the center of mass of the robot. This means that they are capable of producing much less rotation but significantly more translation. This is desired to give the robot forward momentum after the front has been pushed off the ground. See Figure 4.28 below.

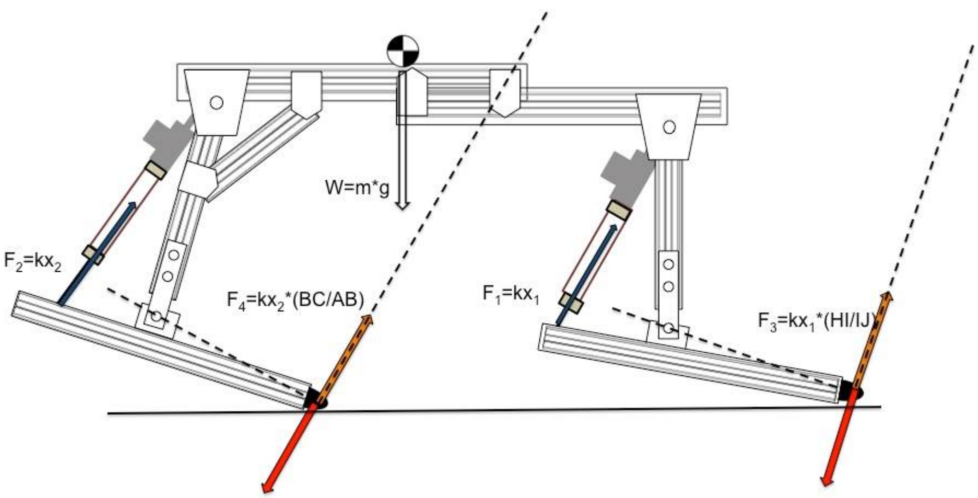


Figure 4.28: The direction of the forces determines the type of gait.

4.6 Electrical System

The electrical system consists of two subsystems: 1) the power system, which includes the power supply, power distribution, regulation, and safety protection systems, and 2) the control system, which includes the microcontroller, sensing, and output control circuitry.

4.6.1 Power Requirements

The expected power requirements of the robot are as follows:

Device	Quantity	Model	Operating Voltage	Total Max. Continuous Current	Total Continuous Power
Hydraulic Pump	1	Remco Fatboy Model A	12 V	25 A	300W
Solenoid Valve	4	Pneumission Brass 1/2" NPT 1-Way	12 V	4 A	48W
Controller	1	Arduino Uno Rev. 3	12 V	0.25 A	3W
Indicators	3	1 Watt LEDs	3.4 V	1 A	3.4W

Table 4.2: Power Requirements for each component of the robot, by type.

All of the electronic devices in the system operate at 12 Volts or less, and the total operating current is less than 30 Amps. The total maximum power consumption is expected to be approximately 350W. Assuming losses from unlisted components, such as voltage regulators, the control board, etc. are negligible, the on-board power supply therefore needs to provide at least 30A at at-least 12V (360W). For a suitable untethered (battery-powered) running time of at-least 15 continuous minutes (see performance specifications), the robot must store at-least 90 Watt-hours (324000 Joules) of energy on-board.

4.6.2 Power Supply

These requirements imply an on-board power supply that is capable of both high-current output and is high-capacity. This supply is also expected to be one of the heaviest single components on the robot, so to meet the total weight requirements, it should be as light as possible, implying a high energy density. In addition, there are practical considerations for size, mounting scheme, recharging time, safety, and reliability. One application that involves similar power and practical requirements to these are unmanned aerial vehicles (UAVs), namely hobbyist-grade remote-control planes and multi-rotors. The standard solution for these machines are Lithium Polymer (LiPo) batteries, and so this solution was adopted for the robot. A 5-cell (18.5V) 8000mAH LiPo battery (Turnigy Nanotech 5S1P, 25C discharge, 924g) was selected to meet the on-board power requirements. This battery was also used for bench top testing in the laboratory, because no bench top power supply capable of delivering a sufficiently high current was available at the time this project occurred. With just one of these batteries, the robot has a theoretical continuous running time of approximately 25 minutes, which the team decided was sufficient for testing purposes.

4.6.3 Speed Controller

The overall frequency of the robot's gait cycle is determined by the net fluid flow rate, which is in turn a function of the speed of the on-board pump. To test different gait cycles at different speeds, it is therefore desirable that the speed of the pump be easily adjustable. A DC Pulse-Width-Modulation (PWM) motor controller was selected (VicTec 40A, 12000Hz, 480W (for 12V input) DC Motor Speed Controller) to adjust the speed of the pump running directly from battery power. The duty cycle of the output could be adjusted from 0% to 100% using an analog potentiometer affixed to the controller.

4.6.4 Voltage Regulation

The chosen LiPo battery has a nominal voltage of 18.5V, however, aside from the pump, all other devices operate on 12V. Therefore, a high-power 12V regulator is required. A DC/DC Step-down (Buck) converter (SMAKN 12V 20A (240W) Waterproof Power Supply Module) was selected to provide the 12V rail. This 12V rail was used for providing power to the solenoid valves, the controller, indicators, sensors, and expandable rails.

4.6.5 Indicators

To monitor the power consumed by the robot, the state of the battery, and to ensure that all components are operating safely, voltage and current sensing is desirable. An automotive voltage/current indicator and corresponding shunt was selected for this purpose (0-100V/A Digital DC Ammeter/Voltmeter with 100A 75mV DC Current Divider Shunt). In addition to monitoring during field-testing, this device was useful when diagnostics on the electrical system were performed.

4.6.6 Fuse Protection

The total current draw for all components of the system was not expected to exceed 30A, so a 30A master fuse was selected to prevent damage and injury from short circuits. The current limit of the fuse was placed as close to the theoretical maximum draw of the robot as possible to minimize damage to critical system components in the event of a current overdraw or simple short-circuit.

4.7 Sensing and Control Circuitry

4.7.1 Sensors

As a legged locomotion platform, the robot requires rich set of sensors for proprioception of its own body and exteroception of the environment which it is operating in. Desirable attribute include ground contact and/or reaction forces from the feet, joint angles, and body spacial orientation and angular velocities. In addition, there are practical parameters that should be monitored to ensure the proper and safe operation of the robot, including the temperatures of critical components, the flow rate of the pump, the fluidic pressure in various parts of the actuation system, and the voltage and current of the power system. These physical quantities, their expected applications, and potential corresponding sensor types are detailed below in Table 4.3.

Physical Parameter	Expected Quantity	Sensor
Joint Angles	8 (Shoulders, knees)	Potentiometer or Encoder
Ground Contact Force	4 (feet)	Spring-loaded potentiometer or load cell
Orientation	3 (DoF)	Inertial Measurement Unit (IMU)
Acceleration	3 (DoF)	Inertial Measurement Unit (IMU)
Flow Rate	1 (Pump output)	Flow Sensor
Temperature	3 (Batteries, pump, control circuit)	Thermocouple, Thermistor
Electrical Current	2 (Batteries, Pump)	Current Sensor
Electrical Voltage	1 (Batteries)	Voltage Sensor
Fluidic Pressure	2 (Pump output, muscle exhaust)	Pressure Transducer

Table 4.3: Each physical quantity can be measured by one or more electronic sensors.

Most commonly available sensors for the above parameters are available with both analog and digital outputs, however, the digital versions are usually higher cost to obtain. The complete list of the selected sensors is detailed in Appendix A.

4.7.2 Control Circuit

Every actuated degree of freedom (Hydro-muscle pair) on the robot is controlled by two, one-way solenoid valves - one input and one output - each of which is in turn activated by a signal from the microcontroller. Custom circuits were constructed to allow the logic-level outputs signals of the microcontroller to activate these inductive loads. Each control circuit consists of one flyback diode and indicator LED (with a current-limiting resistor) in parallel with the solenoid, which is grounded in a controlled manner by an N-Channel MOSFET activated by a digital output of the microprocessor (low-side N-Channel Switch). Although more advanced MOSFET driver circuits are readily available, these custom circuits were sufficient to control the four valves used to control the final robot and were neglible in cost to create.

4.7.3 Microcontroller

There are three primary considerations contributing the the selection of the microprocessor: processing power (speed, memory), available inputs (analog, digital), and available outputs (digital, PWM). For basic gait cycles, controlled by feedforward timing, a processing speed on the order of kilohertz is more than sufficient. For advanced feedback control, more processing power is required for signal processing (for example, filtering and integration for the IMU) and control algorithms, but this processing is not beyond the capabilities of most common modern microprocessors. Basic control of the robot requires two digital outputs per actuated DOF. The final robot used two actuated DOF, and therefore required four digital outputs. One analog input is required per actuated joint (assuming potentiometers), so at least four analog inputs were required.

Based on these parameters, an Arduino Uno was selected as the microcontroller for the robot. The Uno runs at 16MHz, has 6 analog inputs, and 14 digital input/outputs. It is widely available, cost-effective, and well supported. In addition, there are a multitude of expansion "shields" available, and more sophisticated Arduino boards, such as the Arduino Mega, are available as drop-in replacements if additional input, output, or processing power are required.

A diagram of the complete electrical and control output system is shown below (Sensors not shown).

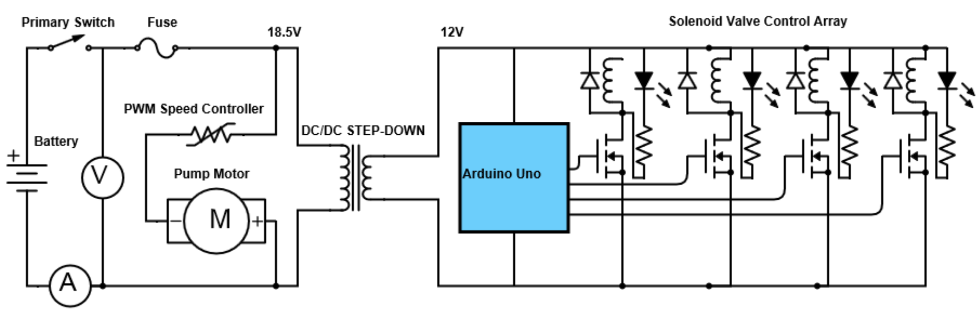


Figure 4.29: Schematic of the primary electrical and control system for the robot

4.8 Software System

The software system is responsible for controlling the robot by reading sensor data, incorporating this data into a control algorithm, and actuating the robot with output signals. The software running on the Arduino activates the actuators of the robot via the electrical control board, which switches the four fluidic control valves on and off. Because the control regime of the hydro-muscles was simplified to toggle between their extreme positions ("extrema-operation") (see the Control subsection of Hydro-muscles section in this chapter), no position control is necessary, and the output of the software is reduced to the determination of timing between inflation/deflation switching. There are two modes of control for achieving this timing: closed-loop and open-loop.

4.8.1 Open-Loop Control

Closed-loop control involved no sensing. The software generates control signals according to predetermined patterns, and these patterns remain unchanged regardless of what is happening in the external evironment. These signal patterns correspond to the phases of operation of the hydro-muscle actuators. For each actuated degree of freedom, there are two digital signals for the two control valves: the inlet-valve (open/close) and the outlet-valve open/close. The valves are normally-closed, and energized by high digital signals. The truth table for these signals and the corresponding hydro-muscle states is shown below in Table 4.4.

Inlet Valve	**Outlet Valve**	**Hydro-Muscle**
Closed (LOW)	Closed (LOW)	Hold (Lock in Previous State)
Closed (LOW)	Open (HIGH)	Deflation (Contract)
Open (HIGH)	Closed (LOW)	Inflation (Extend)
Open (HIGH)	Open (HIGH)	Bypassed

Table 4.4: The relative states of the two valves control the muscle's actuation.

Muscle extension must precede contraction and the bypass state is never used in normal operation (but is useful for purging the fluidic system. See purging procedures section in the Testing chapter). Repeated patterns, such as inflate-hold-inflate-hold, are not useful for extrema-operation of hydro-muscles. A general activation pattern for the cyclic actuation of a hydro-muscle consists of an inflation period, a holding delay, a contraction period, and an intermediate holding time before the start of the next cycle (recovery period). Notice that this Inflate-Hold-Contract-Recover (IHCR) cycle for an actuated DOF can be specified with only four numbers, corresponding to these four quantities of time.

The robot has two actuated degrees of freedom, and in practice, further assumptions and restrictions were applied. The back legs are never contracted before the front legs, because the front legs can only push off the ground by contracting, and if they have not contracted and remain on the ground when the back legs push, they will inhibit forward motion, and the robot will remain in place. It is also assumed that, because the front and back muscles have nearly-identical construction, their inflation times will be appriximately the same, and may be consolidated into one variable. Furthermore, the front and back actuation patterns are synchronized - they have the same total period and start at the same time. With these simplifications, any simple gait actuation pattern can be described with 6 parameters:

1. Inflation (extension) time (t_i) of both muscles
2. Front Contraction Holding Delay (t_{fd})
3. Back Contraction Holding Delay (t_{bd})
4. Front Contraction Time (t_{fc})
5. Back Contraction Time (t_{bc})
6. "Recovery" Holding Delay (t_r)

A gait cycle starts by inflating all muscles, starting at the same time, for duration t_i, and ending at time $t_{inflated}$. Then, after a delay of t_{fd}, the front legs are contracted for a time t_{fc}. Meanwhile, after a delay of t_{bd} from $t_{inflated}$, the back legs are contracted with a time t_{bc}. Finally, after both legs have finished contracting, there is a delay of t_r before the start of the next cycle.

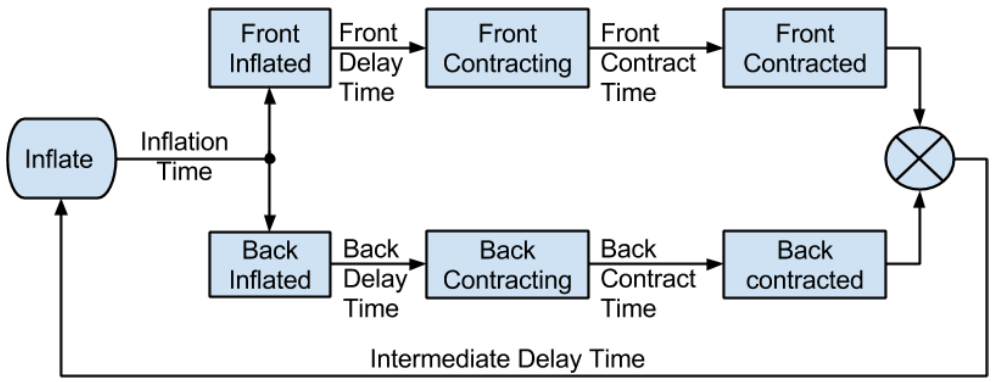


Figure 4.30: The open-loop system flowchart. Timings are the only parameter required.

The basic open-loop controller simply repeats this cycle with particular times indefinitely. Although crude, this method was found to be suitable for demonstrating the capabilities of the robot and testing the basic bounding and hopping gaits, and was used for the majority of experimentation.

4.8.2 Closed-Loop Control

Closed loop control uses sensory feedback to modulate and improve the output signal(s). Several types of open-loop control are possible with the robot, depending on the type of sensors used and the method in which feedback information is incorporated into the control algorithm. Due to the speed of the valve system on the robot and the robot's relatively brief aerial phase during bounding, real-time continuous closed-loop control is not possible; the robot has no means of adjusting any phase of its gait cycle once that phase has begun (all states are binary). For example, it cannot adjust its trajectory in mid-jump. Adjustments made to any of the four parameters describing the gait of the robot will not have an effect until the next time that phase is reached in the cycle.

Example Hopping Controller Consider one possible speed optimization† of the simple hopping gait (described in further detail in Chapter 2.2.1 - Quadruped gait) After pushing up with its front legs, the robot spends some time with its front legs off of the ground before launching forward with the back legs. This time period is potentially wasteful, as the duration of the front aerial period is (nearly) constant, so the longer the wait before launching the back legs, the sooner before the front legs land again, and the less time will be spent moving forward with all four legs off of the ground. By decreasing this delay, hopping becomes more rapid because one of the phases has been shortened. The system also becomes more efficient, because the robot travels a farther distance with each hop. The delay time should therefore be minimized such that the back legs are activated as soon as the front legs leave the ground. In terms of controls, the back leg deflation valve is turned on as soon as a front foot contact sensor indicates a lack of ground reaction force. The discrete, stepwise nature of this type of control implies a state machine as shown in the figure below, rather than a continuous transfer function.

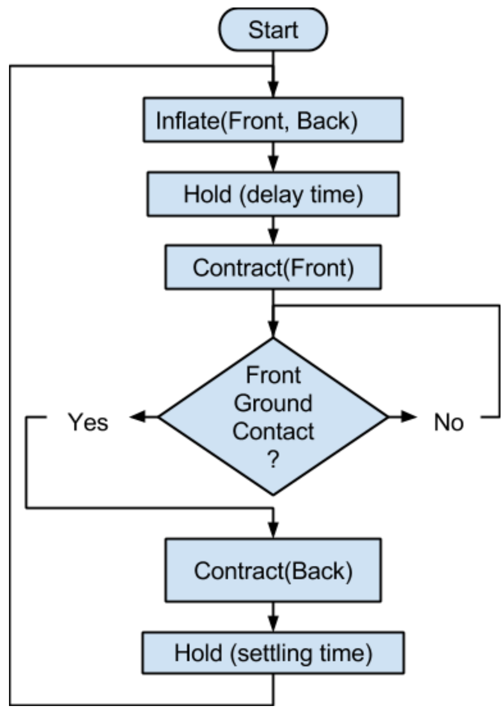


Figure 4.31: The closed-loop system flowchart. Sensors as well as timing are both required parameters.

†All optimizations discussed pertain to maximizing the forward net locomotion velocity of the robot by adjusting the timing parameters of its gait.

Behavior-Based Reactions

All adjustment made to one output parameter only change the robot's behavior for corresponding phase and are based on input from only the previous gait phase. Thus, the controls for each phase ("Behaviors") are effectively separate. Furthermore, the extended past and future are virtually irrelevant to these behaviors. The robot need not have any advanced representation of internal self or external world state or planning algorithm to control simple gaits, and only acts in direct response to sensory input. Almost necessarily, the control software must therefore be based on simple separate reactive protocols. These general paradigms are known as behavior-based and reactive control respectively, and are often combined in this manner. Largely inspired by neurological processes in insects and other simple animals, they have been widely demonstrated as a simple but effective methods enabling mobile robots with limited sensing, processing, and/or actuation capabilities to achieve uncomplicated goals.

Feedforward Control

Feedforward control uses some model of the system to roughly predict the required output. In a closed-loop system, feedback may then be incorporated to more finely adjust output. In this way, the feedforward signal effectively acts as an offset to compensate for predictable perturbations and behaviors of the system, so that feedback control can be finely tuned to compensate for smaller scale discrepancies from the desired behavior (system perturbations). Without the addition of feedback, feedforward control is open-loop. No detailed physical simulation or model of the robot was implemented, as the authors felt that with such rapid kinematic and dynamics adjustments of the physical robot, maintaining the accuracy of this model would become an additional tedium with diminishing returns. However, offsets were implemented in software and added to the timing parameters to compensate for the real switching times of the valves.

Example Bounding Controller The final control algorithm for the bounding gait is similar to that described above for the hopping gait. A ground contact sensor is used to activate both front and back contraction while all legs are in contact with the ground. After all muscles are fully extended, they are all contracted simultaneously. Due to the kinematics and dynamics of the robot, this actuation introduces rotation as well as translation, so the front feet move higher then the back feet and land last. Therefore, it is a reasonable assumption that, if the front legs regain sustained contact with the ground, that the entire robot has landed and settled, and is ready to repeat the gait cycle.

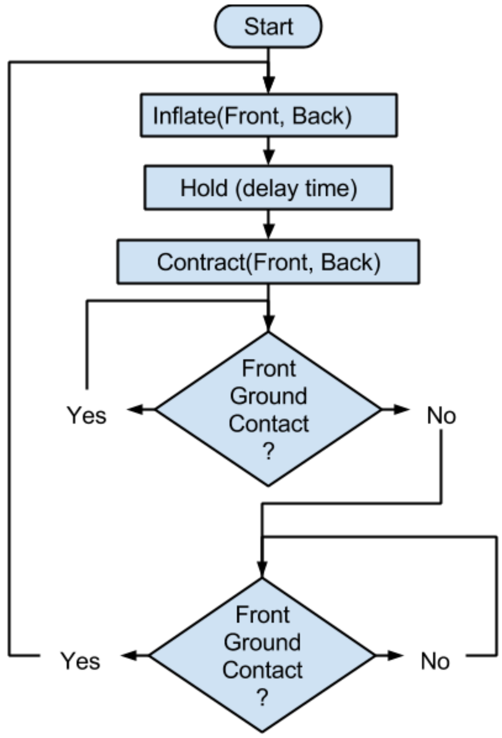


Figure 4.32: A simple bounding controller with ground contact input.

5 - Testing, Iteration, and Results

When the robot achieved operational status, the team started testing the system's response by actuating half of the body; and later on the entire skeleton. This chapter narrates the testing iterations that achieved some level of success, and discusses the parameter values used for each iteration.

5.1 Methodology for Fluidic System Preparation

To test the hydraulic system properly, removal of air from all components of the actuation system was required, which includes the pump, piping, valves and muscles. The procedure (referred to from now on as "purging") changed with each iteration of the actuation system, with each method showing small improvement over the previous. The team developed a method to simplify system saturation by placing a manual valve at a "high-point" (i.e. the location within the fluidic system where air trapped within the fluid would naturally rise to) in the system. A typical purging procedure would be as follows:

With the all other orifices in the system closed, the high-point manual valve is opened. Then, fluid is slowly added to the valve opening while the skeleton is simultaneously re-oriented to assist the air to move towards this valve.

The high-point manual valve is then closed, and all solenoid valves are opened to allow free flow. The pump is then activated and run slowly. As the pump water accelerates liquid through the piping, air accumulates in the highest point of the system, where the manual valve is. Without deactivating the pump, very slowly open the manual valve to let any remaining air bleed out of the system.

This procedure must sometimes be repeated multiple times to ensure that the system is free of air.

5.2 First Test

5.2.1 Setup

The robot was placed on a level surface for single-actuation testing using the hydraulic system described in section 4.4.5, (Figure 7). The purpose of the test was to determine what ground clearance the front legs could achieve. The robot's hind legs were locked in place at 90 degree angle with respect to the body (such that they could not pivot) using M5 bolts. A spring-hanger support was constructed and placed such that a series of small springs were suspending a small portion of the robot's weight so as to minimize damage to the frame in the event of the robot falling to the ground. The springs were not strictly necessary, as a simple piece of untensioned rope or string would have sufficed, however the team felt that the ability to vary the net magnitude of the force that the muscles were subjected to would be advantageous for testing purposes. At this time, the reservoir was not on-board the robot, so the pump drew the working fluid from a basin placed beneath the robots hind-legs. The setup is shown in Figure 5.33.

A simple Arduino program was written for this test. The command sequence to the valve is given below.

1. The input valve opens for 3 seconds of filling time, while the exhaust valve remains closed.

2. The input valve closes, and the system waits (does nothing) for 2 seconds

3. The exhaust valve is opened, releasing the muscle's pressure. The system waits for 3 seconds before repeating the sequence.

The filling time (1) was held constant so that by manually changing the speed control of the pump, different levels of pressurization could be experimented with rapidly. Pressure reached was about 0.89 MPa (130psi).

After all fluidic fittings and attachment points are checked to ensure safe operating conditions, the testing procedure is then performed as follows:

1. The main system power switch is closed, the Arduino is checked for proper activation.

2. The valves are powered and checked to ensure the valve open/close sequence is occurring.

3. When the valve activation cycle reaches the point of opening the pressure inlet valve, the pump is slowly given power.

4. At this point, pressure is sequentially stored and released in small portions by the muscles. The main experimental parameter is now varying the speed of the pump using the DC Speed controller.

5. Components of the system such as the reservoir and muscle fittings are carefully observed to ensure normal operation.

With this simple configuration, system parameters such as pump speed, muscle attachment points, kinematics, valve timings, and weight distribution can be adjusted and observations are now recorded for later analysis.

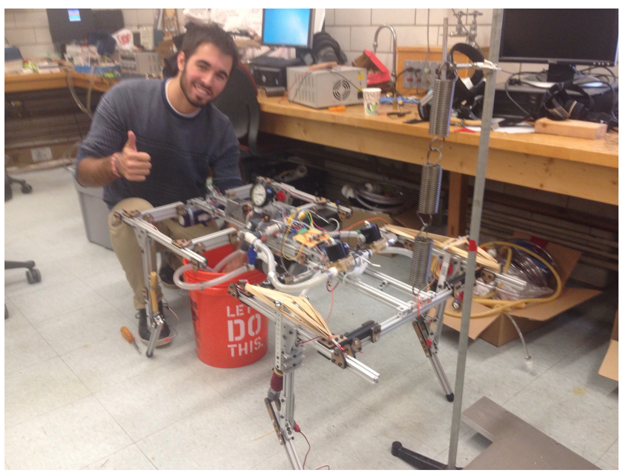


Figure 5.33: A basin is used as the reservoir, and a spring-hanger is connected to the front of HydroDog.

5.2.2 Response

Muscle actuation was successful. The team ran the program and the pump pressurized the muscles. The valves operated well to let water in and out of the system. The front of the body moved up and down as the muscles pressurized and depressurized, signifying that the muscles are strong enough to lift the body. Nevertheless, the muscles' contractions were not powerful enough, and the robot's front feet only achieved about 2 centimeters of ground clearance, as shown on Figure 5.34 .

Figure 5.34: The ground clearance achieved is barely noticeable.

5.2.3 Analysis

The team hypothesized that the muscles used for the front legs did not have a large enough spring constant to launch the robot off the ground significantly. The team also suspected that water's viscosity might affect flow rate exiting the muscle chambers. Fast exhaust flow rate is critical to maximize power output from the muscles. Water flow rate is further discussed in the conclusion.

5.3 Second Test

5.3.1 Setup

The first pneumatic test was performed in a manner identical to the first hydraulic test, using the same spring-hanger apparatus and Arduino valve timing sequence, actuating the front valves, with the purpose of determining what ground clearance the front legs could achieve. The team evacuated water from the entire system. Pressurized air from the laboratory was connected to the robot's inlet pipe to provide constant 0.55 MPa (80 psi) of pressure.

Similar to the hydraulic tests, the system parameters such as muscle attachment points, kinematics, valve timings, and weight distribution can be adjusted and observations are now recorded for later analysis.

5.3.2 Response

Air pressurized the muscles and the system responded well. The front muscles underwent a smaller change in length, which was to be expected with a lower pressure. The release was unexpectedly fast and powerful, and it sent the feet about 3 cm off the ground.

5.3.3 Analysis

Surprisingly, the front feet achieved about the same ground clearance as in the previous test. This is taking into account that the robot was provided a significantly lower pressure because the laboratory only provided 0.55 MPa (80psi). Muscle change in length was noticeably smaller than the previous test, but the release was equally powerful. This means that although the muscles stored less energy in their extension, the same amount of energy was transformed into upwards motion. The team hypothesized that although the muscles in the hydraulic test had more energy, a significant part of that energy was wasted accelerating the water inside the muscles and piping.

5.4 Third Test

5.4.1 Setup

This test was also performed only actuating the front valves, with the purpose of testing how much ground clearance the front feet could achieve. For this test, the team took off the water pump, rendering the robot about 4.5 kg lighter. The team pressurized the tank to 0.79 MPa (115 psi) and ran a program similar the first hydraulic test. During the test, the robot supported its own weight completely, and the air tank was placed a few meters away.

Since the pneumatic pressure source did not require a speed-controlled pump, the only parameter modified was the regulator to vary the pressure between 0.34 and 0.79 MPa. This modified the testing procedure to:

1. The system is disconnected from the external pneumatic pressure source.

2. The main system power switch is closed, the Arduino is checked for proper activation.

3. The valves are powered and checked to ensure that the valve open/close sequence is occurring.

4. When valve operation is verified, the valves are powered off and the pressure source is re-connected.

5. The valves are re-activated and the system begins pressurization.

6. Pressure is sequentially stored and released by the muscles. The main experimental parameter is now varying the position of the pressure regulator.

5.4.2 Response

At about 0.69MPa (100 psi), the muscles elongated nicely when the inlet valve was opened. The robot held its crouched position for about 2 seconds and then released loudly, sending the robot's front half 25 centimeters in the air then bouncing back to its original position. At 0.79MPa (115 psi) the front legs jolted the front half of the body upwards, making it land vertically and flat on its hind legs. This test was the first time hydro-muscles showed promise of enough power to move the robot forward.

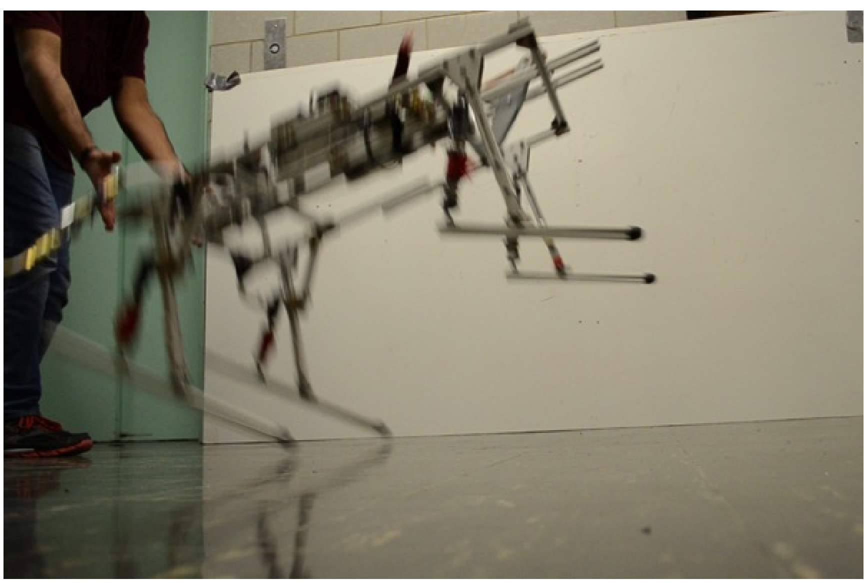


Figure 5.35: The front of the robot achieved about 25cm of clearance.

5.4.3 Analysis

It appears that using air maximizes the conversion of elastic potential energy to robot kinetic energy. The low density of air minimizes the amount of energy required to accelerate it, and the team hypothesized that this is the main reason for the robot's good performance.

5.5 Fourth Test

5.5.1 Setup

After the test, the team prepared the robot for full actuation, with air going into all four muscles. To maximize power output from the back legs, the team prepared muscles that consisted of two large latex tubes in parallel, so each leg would actuate with twice the force of each front leg. These dual-muscles, shown in Figure 4.23 were made by coupling a piping tee with two "L shaped $\frac{1}{2}$" NPT to barbs" plastic fittings. These fittings were hose-clamped to the latex tubes, which were in turn plugged at the other ends and joined by a steel rod.

5.5.2 Response

The robot launched its front half off the ground without any trouble, but the back feet performed little motion and the robot moved forward only about an inch. The forward motion is only noticeable in Figure 5.36 by comparing the position of the front-left leg on the first and last pictures.

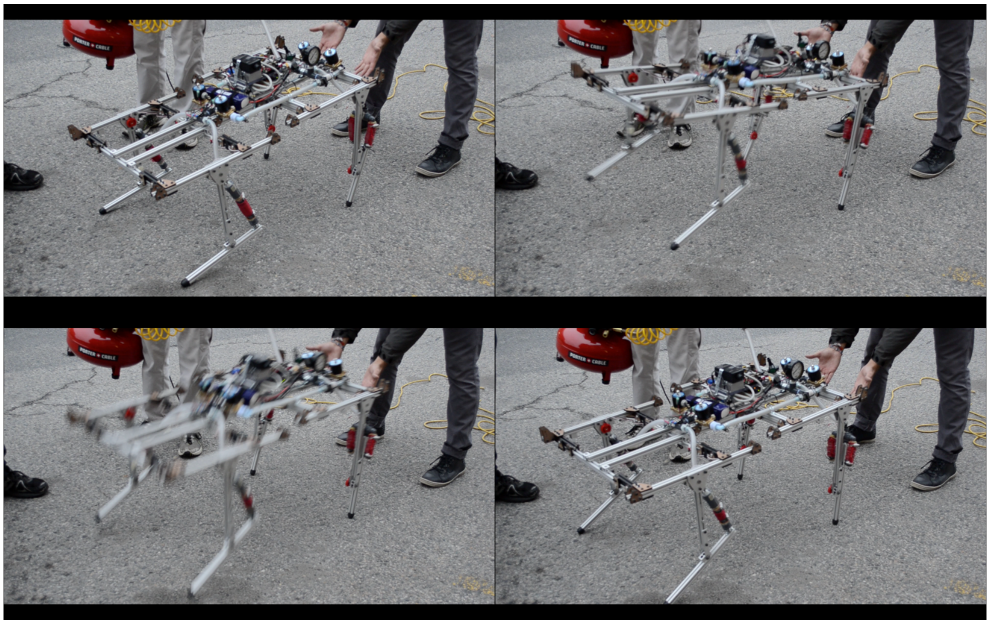


Figure 5.36: Pneumatic testing with dual-rear muscles

5.5.3 Analysis

The back leg's geometry did not allow the feet to perform a large range of motion. The arc traced by the back feet was only 6 cm in length, which did not allow enough distance or time for the legs to accelerate the entire robot forward. The double-muscles only experienced a change in length of about 4 cm, which further minimized the feet's range of motion.

Because these muscles have two tubes each, they increase the consequences of the bottleneck effect. Double-muscles mean that two muscles need to feed air into the same pipe, and then two pipes have to feed air into the same valve. This might have caused the air to exit more slowly from the muscles, which could have affected the legs' dynamics negatively.

For the next tests, the team decided that the length of both the rear-lower legs and the rear muscle arms needed to be significantly longer.

5.6 Fifth Test

5.6.1 Setup

For this test, the team removed the double-muscles from the back legs; and reused two of their latex tubes to fabricate muscles in the same way as the front pair. The team removed the rear-lower leg pieces and replaced them with extrusion more than twice the length. This longer length allowed the foot to perform a much larger range of motion, and gave the muscle a more substantial moment arm from which to pull.

The team programmed the Arduino controller to allow for 3s of filling time, 2s of delay, simultaneous release time and 3s between jumps. The air tank provided 0.86 MPa (125psi) of pressure.

5.6.2 Response

The robot jumped and achieved higher ground clearance that it had before. The front feet jumped up to about 25cm, and the rear feet 10cm. The robot also achieved an appreciable forward motion of about 29cm as seen on Figure 5.37.

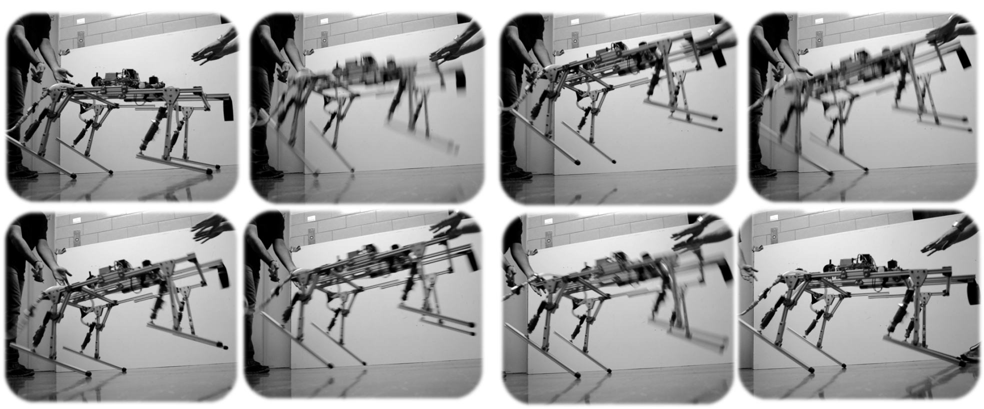


Figure 5.37: The robot achieved very significant clearance and forward motion.

5.6.3 Analysis

The single muscles in the back proved to be a significant improvement to the actuation system. Having a longer arm on both the foot and muscle side of the rear legs resulted in a considerable arc of motion that was able to accelerate the entire body forward, albeit a small distance.This jump was repeatable and consistent.

A continuous gait requires the system be able to fill the muscles completely during air time, so they can fire as they land. The team tested a control program with reduced filling time and 1 MPa (150 psi) of pressure. However, 1 MPa did not suffice to fill the muscles fast enough to create a continuous gait.

5.7 Sixth Test

5.7.1 Setup

In this test the team attempted a gait cycle that is common across legged robot testing. A bounding gait was the original locomotion type the team strived for. The Arduino program allowed for a 150 milliseconds delay between the depressurization of the front legs and subsequent depressurization of the rear legs.

For this test, the skeletal geometry was kept the same as the previous test. The tank provided 0.86 MPa (125 psi) of pressure.

5.7.2 Response

The front of the robot actuated as it had before, lifting the front of the body about 25 cm. The rear legs actuated but were not capable of providing a significant amount of forward motion to the body.

In the sequence on Fig 5.38, the reader can easily see the difference in the initial and final positions of the robot's rear legs. Total forward motion was about 15 cm.

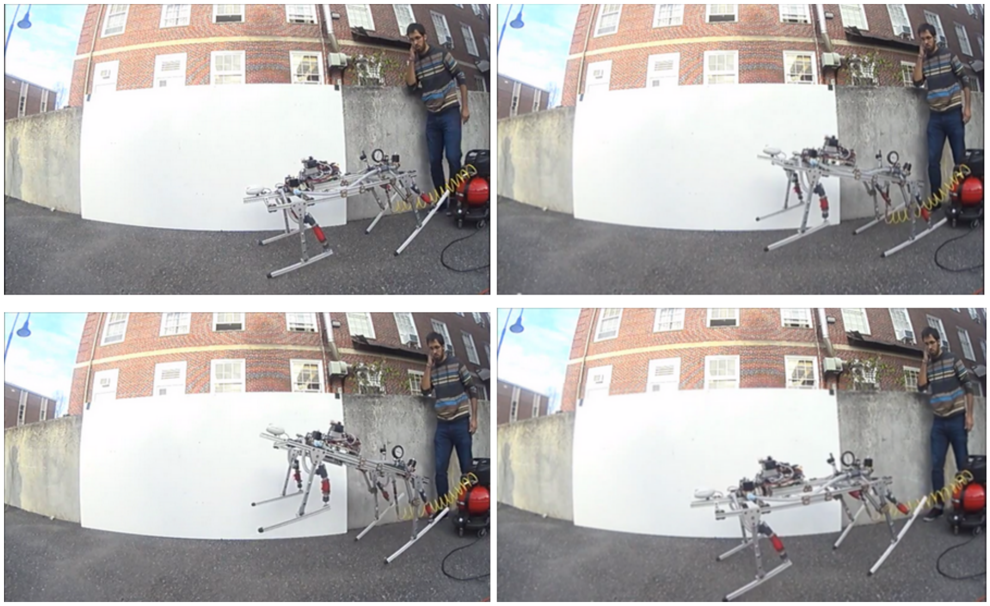


Figure 5.38: The robot moved forward a reasonable amount.

5.7.3 Analysis

The rear legs were not able to provide the body with enough kinetic energy to launch it as the team expected. The team hypothesized that the rear muscles were simply not strong enough for the weight of the robot.

Another possibility is that the rear legs actuated too fast and could not transfer their energy to the entire body. If this is the case, the body might have received an impact rather than an impulse from the back legs, with energy being lost to heat and friction.

5.8 Variables

This section identifies the variables relevant in the testing of the robot. It provides numerical values of these parameters for Test 5. Geometric variables on the skeleton's body are identified on Figure 5.39 and then described below.

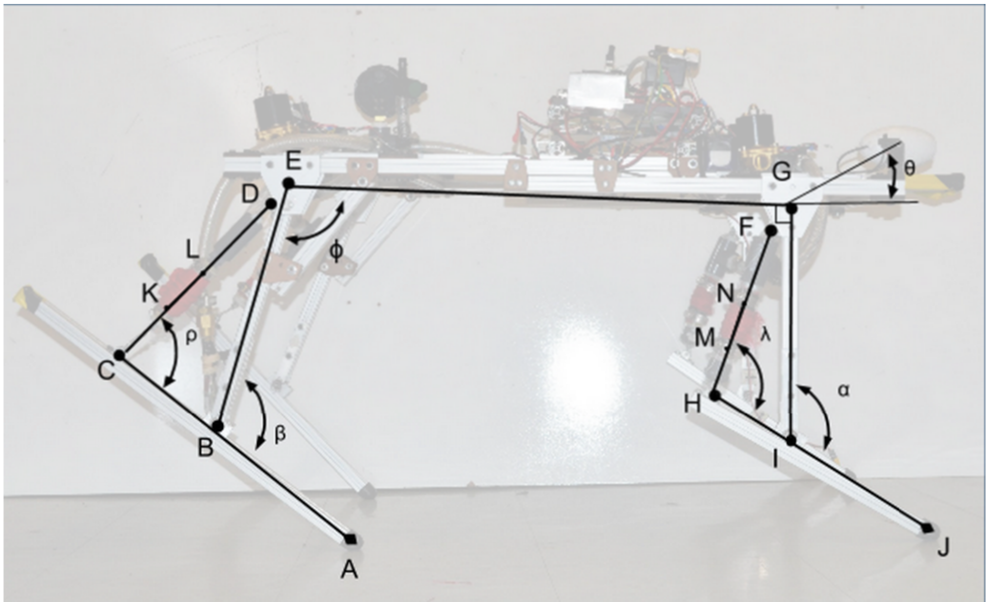


Figure 5.39: Significant geometric variables on the robot's skeleton.

Variable	**Geometric Parameter**
EG	Effective body length measured from hip to shoulder.
BE	Rear upper leg
AB	Rear lower leg
BD	Rear leg knee to muscle attachment
BC	Rear muscle arm
KL	Rear effective muscle length
CD	Rear muscle total length
GI	Front upper leg
IJ	Front lower leg
FI	Front leg knee to muscle attachment
HI	Front muscle arm
MN	Front effective muscle length
FH	Front total muscle length
Θ	Angle between ground and body
ϕ	Angle between body and back upper leg

Table 5.5: Variables describing the geometry of the robot's kinematics.

The dimensions for the final iteration are given in the table below:

BD	**BC**	**KL**	**CD**	**GI**	**IJ**	**FI**	**HI**	**MN**	**FH**
29.2 cm	16.5 cm	7 cm	27.9 cm	29.2 cm	23.5 cm	25.4 cm	11.4 cm	6 cm	22.85

Table 5.6: The final dimensions of the robot were arrived at experimentally.

After the first test, the team prepared the robot for full, all-muscle actuation. In order to maximize power output from the back legs, the team prepared muscles that consisted of two large latex tubes in parallel (See Section 4.3.6), so each leg would actuate with twice the force of each front leg.

6 - Conclusions

6.1 Actuation and Locomotion

After many iterations and tests, the robot demonstrated successful hopping and bounding gaits, both of which included an aerial phase and substantial forward velocity. Thus, robotic locomotion was deemed successful. Likewise, after several generations of design and construction improvements, robust and powerful hydro-muscles were fabricated and tested beyond any pressures and forces previously explored. These tests, along with the robot gaits they generated, further prove the suitability of hydro-muscles as a novel power-augmenting fluidic actuation technology. However, critical differences were observed between tests using water and air as working fluid for the hydro-muscles.

6.1.1 Comparison of Hydraulic and Pneumatic Fluidics

Hydraulics and pneumatics each have important advantages and disadvantages for use in fluidic power transmission on mobile legged robots, especially using hydro-muscle actuation.

Commercially available hydraulic pumps that fall within reasonable size, weight, and power ranges for medium-size mobile robots all have limited capabilities as fluid pressure and flow sources. Therefor, their suitability for powering large-scale hydraulically-actuated mobile robots was initially suspect. However, early bench-tests with hydraulic power transmission were encouraging because the on-board pump and battery were able to provide decent flow rates at high pressures - enough to inflate all four hydro-muscles of the robot to maximum extension on the order of a second. However, further field testing revealed two critical challenges in hydraulic power transmission for hydro-muscles, and fluidic actuators in general, in actuating legged mobile robots. First, the primary advantage of hydraulic fluid is compressibility, which yields higher theoretical efficiencies because energy is not wasted compressing the transmission fluid. However, all known incompressible fluids (liquids, including water and oil) also exhibit two deleterious properties for power transmission in comparison to compressible fluids (gasses, namely air): Firstly, liquids are viscous and more resistant to flow, so more power is required to move a liquid through a fluidic system at a given flow rate than for the equivalent gas flow rate. Secondly, liquids are denser than gasses. A volume of liquid therefor has more mass than the same volume of gas (and this holds even when the gasses are highly compressed by pressure.) With their higher masses, liquids are much harder to accelerate (or decelerate) to high flow speeds. Combined, these factors tend to incur acute dampening on hydraulic power transmissions, decreasing the effective power of the hydro-muslces.

Furthermore, commercially available hydraulic pumps capable of powering sustained gaits are heavy. The pump used for hydraulic experiments added 10lb to the total robot's weight. Due to it's high density, the use of water also directly adds significant weight, especially when stored in an on-board accumulator. In practice, these weight additions, combined with the aforementioned fluidic dampening of hydraulics, proved to be severe hindrances to the robot's mobility. No hydraulic tests achieved a full aerial phase.

For pneumatics, the damping factors identified above are negated. Air has negligible mass and viscosity in the context of consideration as a working fluid for the system. However, no pneumatic pumps exist capable of delivering both the flow-rate and pressure required to run the robot in continuous gaits that would e suitable for on-board use. Such pumps are too large, heavy, or power intensive. Therefor, the move to pneumatics implies a move to off-board power. This has the advantage of eliminating the weight and complexity of on-board fluid pump, but at the sizable practical cost of necessitating an umbilical tether for the robot. Overall, pneumatics were found to be more practical for rapid iteration and testing, and provided the only successful gaits. Hydraulics remain an promising alternative but require further exploration and development.

6.2 Control

Given the limited sensing and actuation capabilities of the robot and the nature of the objective gaits, controls were not considered a large area of difficulty for the project. Open-loop foreword timing controls were found to be sufficient to drive the robot through the two successfully target gaits - bounding and hopping. Feedback behavioral control was demonstrated using ground contact sensing with the hopping gait. The dynamics of the robot observed in each gait closely match those predicted by physical simulation of dynamic models in WorkingModel2D software. Additional sensors are available on the robot for future exploration of more advanced types of feedback and controls.

6.3 Project Logistics - Weight, Cost, and Size

The final weight of the robot is just under 13kg (running on pneumatics), which is well below the project weight constraint of 15kg. The total cost of all components comprising the robot that were bought for the project is approximately \$1,300, which is within the \$1,500. It is also noted that the robot's size, weight, and collapsability, thanks to the reconfigurable construction system, make it highly portable. The researchers transported and demonstrated the robot at two separate events without incident.

6.4 Reconfigurable Test Platform

The 80/20^{TM} 20-series modular T-Slotted aluminum extrusion framing proved met or exceeded all of the requirements for versatility, structural robustness, modularity, extensibility, uniformity, standardization, and continuous adjustability. After adopting this system, the team was able to replace parts and adjust kinematic geometries of the robot in the order of minutes. Combining this reconfigurable with the reliable and extensible electrical and fluidics systems, simple software control algorithms, and the versatility and robustness of hydro-muscle actuators, the robot proved to be highly successful as a reconfigurable robotic kinematics test platform.

6.5 Future Work and Recommendations

Future projects working on HydroDog could concentrate on several developments:

Steering is the very next functionality to develop in the robot. Steering can be achieved by installing 2 DoF shoulder joints with a series elastic system powered by servo motors that allow the robot to steer like a automobile.

Actuating multiple degrees of freedom on each leg will allow for more complex leg motions that could result in better gaits. If this is implemented and fine position control for hydro-muscles is perfected, HydroDog could be capable of climbing up stairs, self-balancing after being disrupted, etc.

Exteroception will render HydroDog capable of mapping its way around objects, a necessary functionality for field operation.

The team believes that water may be a suitable working fluid if much greater consideration is given to the optimization of the fluids system to minimize fluidic dampening, and if the robot is made slightly more powerful and strong overall to accommodate the weight of an on-board hydraulic pump and reservoir.

7 - Outreach and Presentation

Public outreach and presentation is important for the promotion of this project and, by extension, the promotion of the institution and of robotics engineering as a field of research. The research team presented and demonstrated the robot at two events: the Vecna Robot Race and the Cambridge Science Festival.

7.1 Vecna Robot Race

The Vecna Robot race is an annual charity event and competition hosted by Vecna Technologies, a medical robotics company based in Cambridge, MA. The event includes a 5K human run and, new in 2015, a 100m dash for robots. Intended for attract families and children and to promote robotics, the nature of the event is much less formal and competitive than other robotics competitions, such as the Darpa Robotics Challenge. The Vecna race served as an ideal proving ground for hydrodog, while also providing opportunities for outreach and promotion. Prior to the race, the team was interviewed by Reuters, an international news agency, about the role of the race in the Boston-area robotics community. This article was featured in several prominent news outlets, including the New York Times website and the Boston Globe.

Figure 7.40: The HydroDog project team at the Vecna Robot Race

The event itself was considered a promotional success, although HydroDog did not complete the 100m dash. Due to the limited flow-rate of the pneumatic compressor and the non-optimal kinematics in-use at the time the robot's forward locomotion was hindered and noncompetitive with the other robots in it's heat. However, Hydrodog did have the distinction of being the only legged robot in attendance and the research team was interviewed by the MIT ALumni Association.

7.2 Cambridge Science Festival 2015

The Cambridge Science Festival is an annual event across Cambridge featuring a variety of science and technology themed events, activities, and exhibits for kids, families, and enthusiasts. Hydrodog was features in the "Robot Zoo" section, along with other projects from Popovic Labs at WPI. After dozens of live demonstrations and a pubic introduction and explanation of the robot, HydroDog was among the most popular robots at the event.

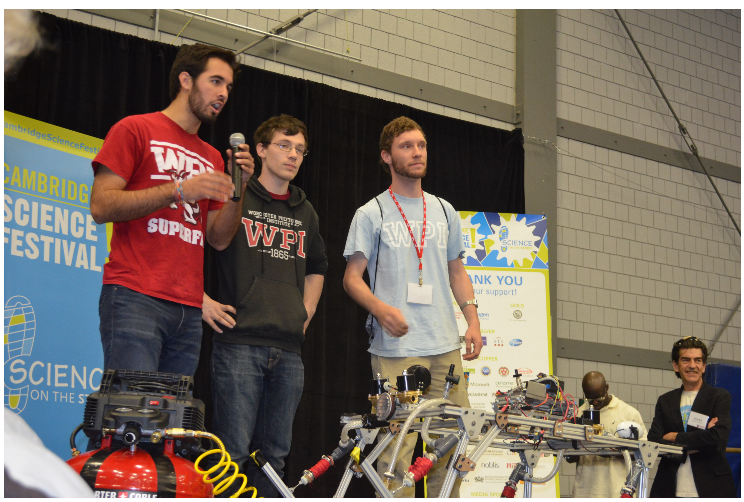


Figure 7.41: The HydroDog team presenting at the Cambridge Science Festival

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.1 Appendix

.1.1 Code Example

```
/******************************************************************************

HydroDog MQP Bounding Gait Controller

Author: Daniel Fitzgerald

This program runs onboard the HydroDog Quadruped Robot MQP.
It controls the bounding gait by reacting to ground contact on the front feet.

******************************************************************************/

// Pinout for the fluidic control valves that allow fluid in and out of the
   hydro-muscle actuators.
// The left and right legs are connected as pairs, and controlled as one
   actuated Degree of Freedom (DOF).
int back_inlet_pin =  9;
int back_outlet_pin =  10;
int front_inlet_pin =  6;
int front_outlet_pin = 5;

// Pinout for the front foot contact sensor.
// This sensor is a toggle switch with pull-down resistor which is closed (LOW)
   when the front feet are contacting the ground.
int front_contact_pin = 2; // Digital Pin #2 (can trigger interrupt)

// General Control Parameters (all times in milliseconds)
int inflation_time = 800;   // The time the muscles are given to pressurize
int charge_delay = 100;     // The delay between the end of pressurization and
   the start of contraction
int intermediate_delay = 100; // The delay between the ed of contraction of one
   cycle and the begining of inflation for the next.

// Threshold for reaction
int contiguous_settling_time = 1000; // the minimum continuos time that the
   front legs have been on the ground before the robot will be considered to
   be in a "settled state" and is ready to jump again.

// Feedforward control parameters. Valves take a finite time to fully switch
   state.
int valve_close_delay = 30;
int valve_open_delay = 10;
```

```
void setup() {

  // Declare the valve control pins as outputs.
  pinMode(back_inlet_pin, OUTPUT);
  pinMode(back_outlet_pin, OUTPUT);
  pinMode(front_outlet_pin, OUTPUT);
  pinMode(front_inlet_pin, OUTPUT);

  // Declare the ground contact sensor pins as inputs.
  pinMode(front_contact_pin, INPUT); // foot contact sensor pin as input

  // open the serial port at 9600 bps:
  Serial.begin(9600);

  // When the robot is first turned on, ensuring the muscles aren't pressurized
      (for safety)
  open_exhaust_all();

  // Inflate all muscles for the first hop
  open_inflate_all();
  delay(inflation_time);
  close_inflate_all();

  // Small delay before starting the first gait
  delay(charge_delay);
}

void loop() {

  // JUMP!
  open_exhaust_all();

  // Poll the contact sensor to wait for the front legs to come off the ground
      (indicating that the front has achieved aerial phase.)
  while(front_has_contact()){
    delay(10); // small polling period
  }

  // As soon as the front takes off, stop contracting the muscles and start
      filling them again.
  close_exhaust_all();
  open_inflate_all();

  // Wait for the front legs to settle on the ground for at-least
      *contiguous_settling_time*.
  long start_pressurization_time = millis();
  long contact_time_ms = 0;
  while (contact_time_ms < contiguous_settling_time){ // polling loop
```

```
    delay(1);
    if (front_has_contact()){
      contact_time_ms++; // still in contact with the ground - increment the
          contiguous contact time
    }else{
      contact_time_ms=0; // lost contact with ground (bounce) - reset the
          contiguous contact time
    }

    // If the elapsed time since the muscles started inflating is equal to or
        greater than the time it takes to completely inflate them, stop
        inflating them.
    if ((millis() - start_pressurization_time) >= inflation_time){
      close_inflate_all();
    }
  }

  // If the muscles are still inflating, let them fill up for the remaining
      time.
  int remaining_inflation_time = millis() - start_pressurization_time -
      inflation_time;
  if (remaining_inflation_time > 0){
    delay(remaining_inflation_time);
  }

  // Loop to the next gait cycle after a short delay
  delay(intermediate_delay);
}

// Valve switching commands
void open_front_out(){
  digitalWrite(front_outlet_pin, LOW);
  delay(valve_open_delay);
}
void close_front_out(){
  digitalWrite(front_outlet_pin, HIGH);
  delay(valve_close_delay);
}
void open_back_out(){
  digitalWrite(back_outlet_pin, LOW);
  delay(valve_open_delay);
}
void close_back_out(){
  digitalWrite(back_outlet_pin, HIGH);
  delay(valve_close_delay);
}
void open_front_in(){
  digitalWrite(front_inlet_pin, LOW);
  delay(valve_open_delay);
```

```
}
void close_front_in(){
  digitalWrite(front_inlet_pin, HIGH);
  delay(valve_close_delay);
}
void open_back_in(){
  digitalWrite(back_inlet_pin, LOW);
  delay(valve_open_delay);
}
void close_back_in(){
  digitalWrite(back_inlet_pin, HIGH);
  delay(valve_close_delay);
}

// Close the outlets to all muscles (stop contracting).
void open_exhaust_all(){
  Serial.print("START EXHAUSTING ALL...\n");
  digitalWrite(front_outlet_pin, LOW); //Make sure that both OUT valves are off
  digitalWrite(back_outlet_pin, LOW);
  delay(valve_open_delay);     //Delay to give the valves time to close
}

// Opens the outlets of all muscles (start contracting).
void close_exhaust_all(){
  Serial.print("STOP EXHAUSTING ALL...\n");
  digitalWrite(front_outlet_pin, HIGH); //Make sure that both OUT valves are off
  digitalWrite(back_outlet_pin, HIGH);
  delay(valve_close_delay);     //Delay to give the valves time to close
}

// Opens the inlets to all muscles (start inflation).
void open_inflate_all(){
  Serial.print("START PRESSURIZING ALL...\n");
  digitalWrite(front_inlet_pin, HIGH); //Make sure that both OUT valves are off
  digitalWrite(back_inlet_pin, HIGH);
  delay(valve_open_delay);     //Delay to give the valves time to close
}

// Closes the inlets to all muscles (stop inflation).
void close_inflate_all(){
  Serial.print("STOP PRESSURIZING ALL...\n");
  digitalWrite(front_inlet_pin, LOW); //Make sure that both OUT valves are off
  digitalWrite(back_inlet_pin, LOW);
  delay(valve_close_delay);     //Delay to give the valves time to close
}

// Returns True when the front legs are in contact with the ground, False
   otherwise.
boolean front_has_contact(){
```

```
  digitalRead(front_contact_pin);
}
```